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Introduction

Substantial evidence suggests that a UV Spectrally Absorbing Material (UV-SAM) exists on Triton's surface (e.g., Stern-1993; Croft, et al. 1994). This evidence is found in the positive slope in Triton's spectrum from the UV to the near-IR, and the increasing contrast in Triton's light curve in the blue and UV. Although it is now widely-thought that UV-SAMs exist on Triton, little is known about their distribution and spectral properties.

The goal of this NDAP Project is to determine the spatial distribution and geological context of the UV-SAM material. We hope to determine if UV-SAMs on Triton are correlated with geologic wind streaks, craters, calderas, geomorphic/topographic units, regions containing (or lacking) volatile frosts, or some other process (e.g., magnetospheric interactions). Once the location and distribution of UV-SAMs has been determined, further constraints on their composition can be made by analyzing the spectrographic data set.

To accomplish these goals, various data sets will be used, including Voyager 2 UV and visible images of Triton's surface, IUE and HST spectra of Triton, and a geologic map of the surface based on Voyager 2 and spectrophotometric data. The results of this research will be published in the planetary science literature.

Research Report

We began this project by performing a global survey of Triton's surface to look for large scale UV-SAMs regions. The primary data set used for this task consisted of Voyager 2 ISS mosaic images of Triton's surface made using the UV (3500 Å) and CLEAR (5600 Å) filters (Figure 1). These mosaics cover mainly the equatorial region of the satellite.

The UV-SAM on Triton has a relatively low UV and high visible albedo. Therefore, the locations of preferentially-high UV-SAM concentrations should correspond to regions where the UV-filter brightness is anti-correlated with visible brightness in the Voyager mosaics.

Two methods were used to accomplish this comparison. First, the UV and CLEAR mosaics were converted to contrast maps to enhance their albedo variations. This was done by subtracting an average brightness followed by normalization by the average. Potential UV-SAMs regions were further enhanced by dividing the difference of the contrast mosaics by their sum. The resulting "correlation map" shows broad regions, particularly near 0° longitude, that we conclude may represent the first identification of UV-SAM source regions on Triton.

Next, a second, more quantitative, method was used to determine if the regions detected by the method described above are real indications of UV-SAMs. To do this we looked for a correspondence between (i) regions in the UV mosaic that are between 1 and 2 standard deviations (σ) darker than the average albedo and (ii) regions in the CLEAR mosaic that are 1-2 σ brighter than average. The results of this analysis show that the possible UV-absorbing region around 0° longitude also passes this test, confirming the findings of the first method described above.

It was recognized that the global comparisons described above could miss small-spatial-scale UV-SAM regions. Therefore, small sub-regions ranging in size from $\approx 500 \times 500$ km to $\approx 2000 \times 2000$ km (at the equator) were tested for anti-correlated albedo behavior. Using a sub-region size of $\approx 2000 \times 2000$ km revealed a distinct UV-SAM region $\approx 700 \times 1900$ km in size centered near +20° longitude and -25° latitude (Figure 2). Significantly, this region is colocated with a distinct geological unit on Triton containing maculae (spotted terrain) and wind streaks, as identified in a geologic map provided by Col Schenk. Furthermore, the UV-SAM region abuts a highly reflective region possibly containing clean ices, suggesting a possible volatile transport relationship. We presented these results at a recent scientific meeting (Flynn et al., 1995; see Appendix 1) and they have been written up for publication in two papers (Flynn

et al., 1995; Stern et al., 1995; see Appendix 2).

Publications and Talks

Flynn, B., S. A. Stern, B. Buratti, P. Schenk, and L. Trafton, 1995. The Spatial Distribution of UV-Absorbing Regions on Triton. International Conference on Solar System Ices, Toulouse, March, 1995 (abstract and talk).

Flynn, B., S. A. Stern, B. Buratti, P. Schenk, and L. Trafton, 1995. The Spatial Distribution of UV-Absorbing Regions on Triton. *Planetary and Space Science* (submitted).

Stern, S. A., L. M. Trafton, and B. Flynn, 1995. Rotationally Resolved Studies of the Mid-Ultraviolet Spectrum of Triton. *Astron. J.*, **109**, 2855-2867.

Figure Captions

Figure 1. Mosaic constructed from 10 Voyager 2 ISS images taken through the UV (3500 Å) filter. The images were taken in August 1989 prior to closest approach to Triton.

Figure 2. Correlation map constructed using $\simeq 2000 \times 2000$ km sub-regions, revealing a distinct UV-SAM region $\simeq 700 \simeq 1900$ km in size and centered near $+20^\circ$ longitude and -25° latitude.

Triton, UV Filter

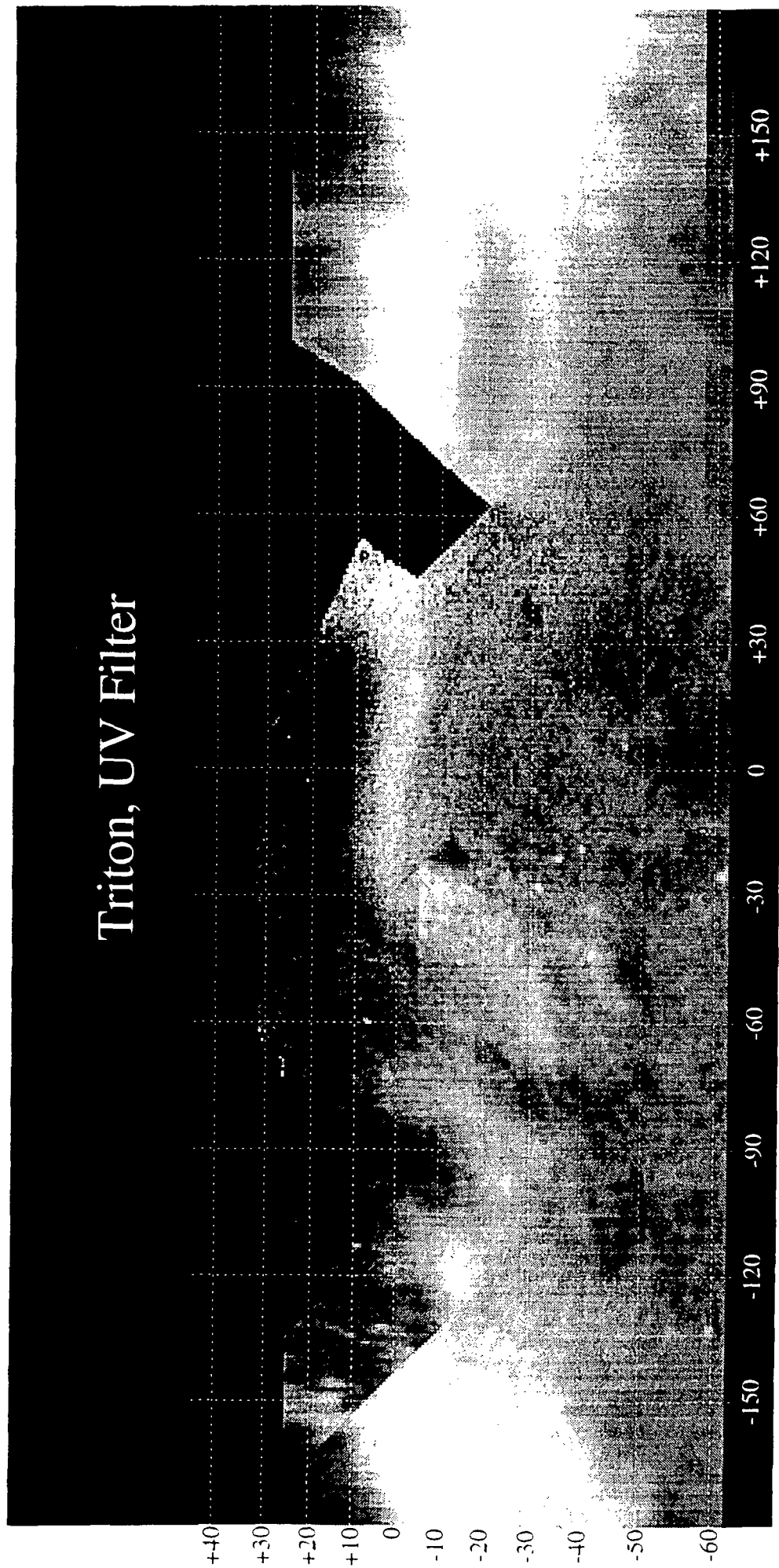


FIG. 1

Clear 5%>Average, UV 5%<Average

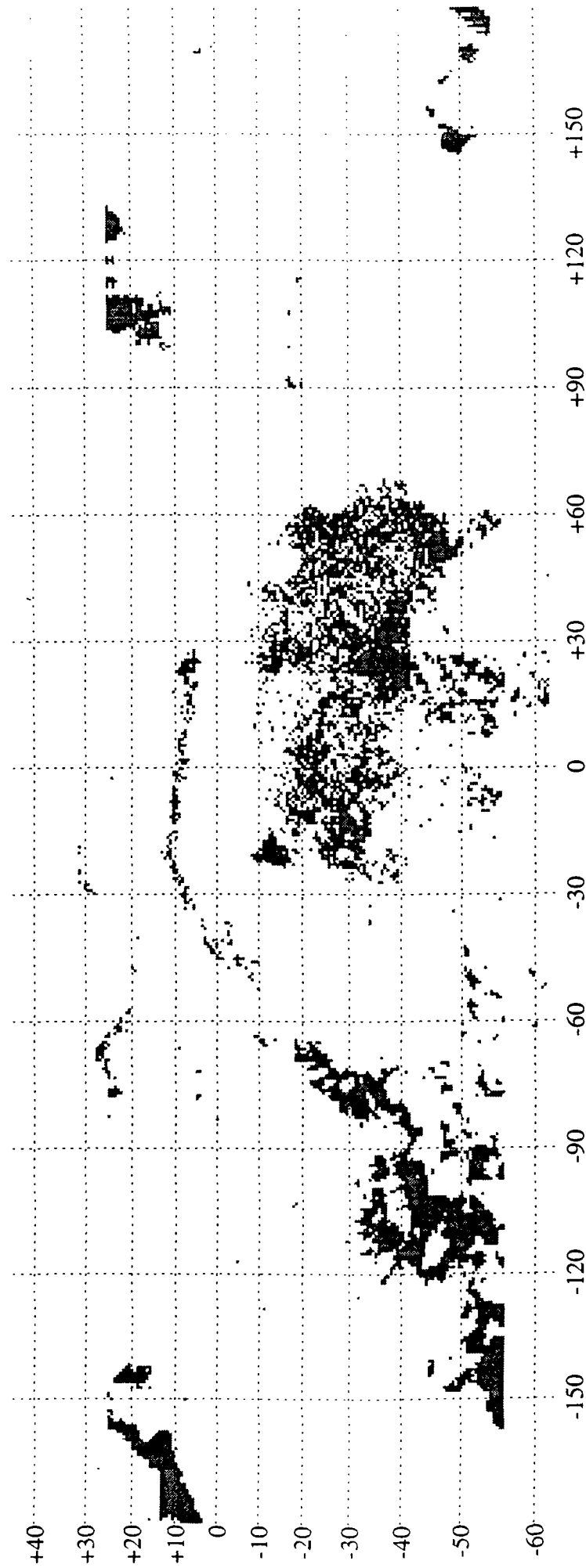


FIG 2

Appendix 1

THE SPATIAL DISTRIBUTION OF UV-ABSORBING REGIONS ON TRITON

Flynn B., Stern A., Buratti B., Schenk P., and Trafton L.

Substantial evidence suggests that a UV Spectrally Absorbing Material (UV-SAM) exists on Triton's surface. This evidence is found in the positive slope in Triton's spectrum from the UV to the near-IR, and the increasing contrast in Triton's light curve in the blue and UV. Although it is now widely thought that UV-SAMs exist on Triton, little is known about their distribution and spectral properties.

We present the first results of an ongoing study using Voyager 2 images, IUE and HST spectra, and a geological map of Triton to determine the spatial distribution and geological context of the UV-SAMs on Triton. The goal of this project is to determine if UV-SAMs on Triton are correlated with geologic wind streaks, craters, calderas, geomorphic/topographic units, regions containing (or lacking) volatile frosts, or some other process (e.g., magnetospheric interactions). The study of the Voyager imaging data is taking place in two phases: (1) Search for large-scale (10s-100s of km) UV-absorbing regions using global, medium-resolution maps of Triton; and (2) a study of high-resolution UV-visible image pairs to look for UV-SAM regions on a small spatial scale (~ 10 km).

As a result of Phase 1 of our study, we find a distinct UV-dark region $\simeq 700 \times 1900$ km in size and centered near $+20^\circ$ longitude and -25° latitude. The region correlates well with a geological unit containing maculae (spotted terrain) and wind streaks. The UV-absorbing region abuts a high-albedo region, lying just to north, that may be composed of relatively uncontaminated, clean ices. The positioning of the UV-dark region and the clean-ice region suggests a possible dynamic relationship involving volatile transport between the two units.

Appendix 2

THE SPATIAL DISTRIBUTION OF UV-ABSORBING REGIONS ON TRITON

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1. Introduction

Substantial evidence suggests that UV-absorbing materials (UVAs), which exhibit a dramatic decrease in reflectivity below $\sim 4000 \text{ \AA}$, exist on Triton's surface (cf. Croft et al., 1995). This evidence is found in the positive slope in Triton's spectrum from the UV to the near-IR, and the increasing contrast in Triton's light curve in the blue and UV (Hillier et al., 1991; Stern, 1993; Stern et al., 1995). The volatiles known to be on Triton's surface (N_2 , CH_4 , CO) do not show such spectral behavior, and neither does the dominant crustal/mantle material, H_2O ice (Wagner et al., 1987). However, laboratory studies show that many non-icy materials are UVAs, including a variety of organics (Cruikshank et al., 1991; Thompson et al., 1987), many sulfur compounds (Nash, 1980; Nash and Fanale, 1977), NaCl and some sodium nitrates (Nash and Fanale, 1977), and certain refractory minerals (Wagner et al., 1987).

We present here the first results of a study intended to characterize the nature of UVAs on Triton. The goals of this study are to: (1) Determine the location and distribution of UVAs on Triton; (2) determine if the UVAs are associated with any particular geologic or geomorphic units; (3) constrain the composition of the UVAs; (4) compare the UVA distribution to the expected locations of volatiles and lag deposits predicted by volatile transport models; and (5) to constrain the

lifetime and required production rates of UVAs on Triton.

The results we present in this paper show a broad, distinct UVA region centered near $+20^\circ$ longitude and -25° latitude, which is $\approx 700 \times 1900$ km in size. The region correlates well with a geological unit containing maculae (spotted terrain) and wind streaks. The UV-absorbing region abuts a high-albedo region, lying just to the north, that may be composed of relatively uncontaminated, fresh ices. The positioning of the UV-dark region and the clean-ice region suggests a possible dynamic relationship involving volatile transport between the two units.

2. Data Analysis

To accomplish the goals of this study, various data sets are required, including Voyager 2 UV and visible images of Triton's surface, IUE and HST spectra of Triton, and a geologic map of the surface based on Voyager 2 imaging and spectrophotometric data.

The primary data set used to search for UVA regions on Triton consists of Voyager 2 image mosaics of Triton's surface constructed from pre-encounter, narrow-angle images taken through the UV (3500 Å) and Clear (5600 Å) filters (Table 1; Figure 1). Each image in the mosaics was photometrically corrected and converted to normal albedo.

The UV and Clear filters were chosen to take advantage of the different spectral characteristics of UVAs and the volatile frosts on Triton. Specifically, because of their relatively low-albedo in the spectral region containing the UV filter, UVA regions should appear relatively dark in the UV images, whereas regions containing uncontaminated volatile frosts should appear bright in both filters. UVAs may also appear brighter than average in the Clear filter because of their high albedos in that spectral region.

In order to identify regions containing UVAs, we searched for areas that are darker than average in the UV mosaic and brighter than average in the Clear mosaic. However, simply taking global averages of the mosaics could result in small-scale UVA regions being missed. Therefore, to avoid selecting against any particular size range, we used search areas of sizes ranging from $\approx 500 \times 500$ km to $\approx 2000 \times 2000$ km (at the equator), stepping the search window across the mosaics to search all available regions of Triton's surface. We used stepping sizes of $\frac{1}{2}$ the width of the search window and, additionally, $\frac{1}{4}$ -width in the case of the ≈ 2000 km window. The portion of Triton's surface falling within a search window was tested for areas darker than average in the UV mosaic and brighter than average in the Clear mosaic. The average value corresponds to the average albedo within the

search window. We used various thresholds of brightness or darkness relative to the average albedo of 5%, 7%, and 10%, in relative (not absolute) albedo units to identify possible UVAs. A relative albedo difference of 10% corresponds to approximately one standard deviation, as computed from each mosaic globally. Similarly, in order to identify regions containing uncontaminated, fresh volatile frosts we searched for regions that are at least 10% (approximately one standard deviation) brighter than average in both mosaics. We chose this higher threshold because fresh frosts should appear as the brightest material in both the UV and Clear filters (Wagner et al., 1987).

3. Discussion

As a result of our search, we identify for the first time a distinct UVA region on Triton. This region extends from -30° to $+60^\circ$ in longitude and -40° to -10° in latitude and its approximate dimensions are 1900×700 km (Figure 2). The region is easily discernable using a search window of $\simeq 2000$ km in size and a threshold of 5% darker than average in the UV mosaic and 5% brighter than average in the Clear mosaic, and is still visible using a 7% threshold. The UVA region identified in Figure 2 is the only area on the portion of Triton's surface mapped in Figure 1 that remains unchanged when the brightness/darkness threshold is increased from 5% to 7%.

Searching for areas of Triton's surface that are greater than 10% brighter than average using a $\simeq 2000$ km search window has revealed several distinct regions possibly containing fresh frosts (Figure 2). One region, ranging from -30° to at least $+40^\circ$ in longitude and -10° to $+10^\circ$ in latitude, lies just north of and abuts the UVA region described above. The adjoining positions of the UVA region and the bright region suggests a possible dynamical relationship, discussed below.

To place the two regions identified in Figure 2 into a geological context, we have compared them with a map of geological units on Triton's surface (Figure 3). The UVA region identified in Figure 2 is located within the geologically mappable region of Triton imaged at good resolution by Voyager 2 in 1989. The outline of the UVA region corresponds closely with a well-defined geologic unit (Figure 3) mapped by both Croft et al. (1995) and Schenk and Moore (1993). Schenk and Moore termed this unit *bright spotted terrain* (labeled *m* in Figure 3). This unit consists of relatively dark material organized as irregularly shaped spots (or maculae) ranging in size up to ~ 50 km across (Figure 4). Maculae are separated by relatively bright material. Most of the dark wispy surficial deposits, sometimes referred to as "wind streaks" are also located within this terrain. Just to the

north of the *m* terrain, is a unit sometimes referred to as the *bright equatorial fringe* (Croft et al., 1995). The bright region identified in Figure 2 corresponds spatially to this geologic unit.

The origins of maculae are unclear. Schenk and Moore (1993) speculate that they may be erosional remnants of an originally more contiguous deposit, or that they are constructional, formed by multiple extrusive events. The bright material within the *m* terrain may be relatively easily eroded (Schenk and Moore, 1993). A narrow fracture extends into this terrain from the north (Figure 4). It is obscured by the darker maculae, but is sometimes (but not always) visible through the bright intermaculae material. One plausible interpretation is that both bright and dark materials buried this preexisting fracture, but that the bright material has been partially eroded, exposing the old fracture in various locations (Schenk and Moore, 1993). We discuss one possible seasonal transport scenario in more detail below.

Triton's seasons are complicated by the precession of Triton's orbit (Dobrovolskis, 1980; Harris, 1984), which causes the seasonal extremes to vary sinusoidally (Trafton, 1984). Triton is currently approaching a maximum solstice, due early in the next century, which may be soon followed by a seasonal extreme in the volatile transport cycle, delayed by one thermal lag-time. Although the large size of the southern cap at this phase of the seasonal cycle is puzzling, it should continue to sublime, increasing the atmospheric bulk and driving the transport of volatiles through the atmosphere towards the northern hemisphere. Areas which become denuded of volatiles, or thin enough for translucence to reveal the non-volatile surface, or even thin enough to reveal the non-seasonally deposited volatile surface, are expected to darken. This is partly because of the role of EUV radiation plus solar and galactic cosmic rays in producing dark residues from atmospheric and ice hydrocarbons which cycle to the bottom of the seasonal deposit, explaining both Triton's and Pluto's brightness (Stern et al., 1988). Such residues are likely to be darker in the UV than in the visible owing to the greater strength of electronic absorption coefficients in the UV.

Triton's UVA may be such a region where the hydrocarbon deposits are most exposed owing to the seasonal cycle and the long term tendency for the greater annual equatorial insolation to drive surface volatiles from Triton's equator towards the poles. Topography and geology may explain the longitudinal confinement. The bright region identified in Figure 2 may be at sufficiently low insolation to be a region of net deposition of volatiles, particularly if this region has a higher albedo in the visible than does the UVA. The fresh frost would help to hide the darker deposits in both wavelength regions, especially if they are porous. Multiple

scattering would help to raise the albedo because much of the light would be diffusely reflected before it can be absorbed.

4. Summary

Using mosaic maps of Triton's surface made with images taken through the Voyager 2 UV and Clear filters, we have sought to: (1) Distinguish between surface units containing UV-absorbing (UVA) materials and fresh volatile frosts; (2) place any such identified regions into a geological context; and (3) to interpret these regions in terms of seasonal volatile transport scenarios.

In pursuit of these goals, we have identified both a region possibly containing involatile UVA materials and an adjoining region possibly covered by uncontaminated, fresh frosts. The UVA region correlates well with a distinct geological unit on Triton containing maculae and wind streaks. The location of these two regions suggests that they might be dynamically linked through the transport of volatiles between them.

5. Acknowledgements

We thank Joel Mosher at the NASA Jet Propulsion Laboratory for constructing the mosaic images, and Clark Snowdall for assisting in data analysis. This research was supported by a grant from the Neptune Data Analysis Program of the National Aeronautics and Space Administration.

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Table 1: Triton Mosaic Images^a

Clear Images	UV Images
1127755	1126642
1129147	1127814
1129855	1129212
1130545	1129920
1131314	1131400
1133837	1133923
1134834	1134920
1137148	1138715
1137709	1139313
1138709	1139319
1139303	1137727
1139330	1137245
1139340	

(a) All images taken with the Voyager 2 narrow-angle camera.

7. Figure Captions

Figure 1. UV and clear mosaic images used to search for UV-absorbing regions and areas containing uncontaminated, fresh volatile frosts. *Top Panel:* Mosaic constructed from 12 Voyager 2 images taken through the UV (3500 Å) filter. *Bottom Panel:* Mosaic from 13 images taken with the Clear (5600 Å) filter. The images were taken in August 1989 prior to closest approach to Triton. The images used in the mosaics are given in Table 1.

Figure 2. *Top Panel:* Correlation map constructed using a search window $\simeq 2000 \times 2000$ km in size (at the equator), revealing a distinct UV-absorbing region $\simeq 700 \times 1900$ km in size and centered near $+20^\circ$ longitude and -25° latitude. The 5% threshold refers to relative, not absolute albedo units. *Bottom Panel:* Correlation map showing a region that is at least 10% brighter than average in both the UV and clear filters, indicating the presence of uncontaminated volatile frosts. The bright region abuts the UV-absorbing region, which lies just to the south. The adjoining positions of the two regions suggests a possible dynamical relationship.

Figure 3. Geological sketch map of Triton, based on mapping by Croft et al. (1995), Schenk and Jackson (1993), and Schenk and Moore (1993). The map covers -60° to $+90^\circ$ longitude and extends from $+30^\circ$ latitude to the south pole. The UV-absorbing region shown in Figure 2 corresponds well with the position and size of a geologic unit labeled *m* and previously referred to as *bright spotted terrain*. The bright region identified in Figure 2 corresponds to a geologic unit sometimes referred to as the *bright equatorial fringe* and may contain uncontaminated volatile frosts.

Figure 4. Close-up of region of Triton's surface containing maculae and wind streaks. The UV-absorbing region identified in Figure 2 corresponds to this geologic unit. The brighter material surrounding the darker maculae (spots) may be eroding, leaving the darker material exposed. See the text for further discussion. Image courtesy of the NASA Jet Propulsion Laboratory.

Triton, UV Filter

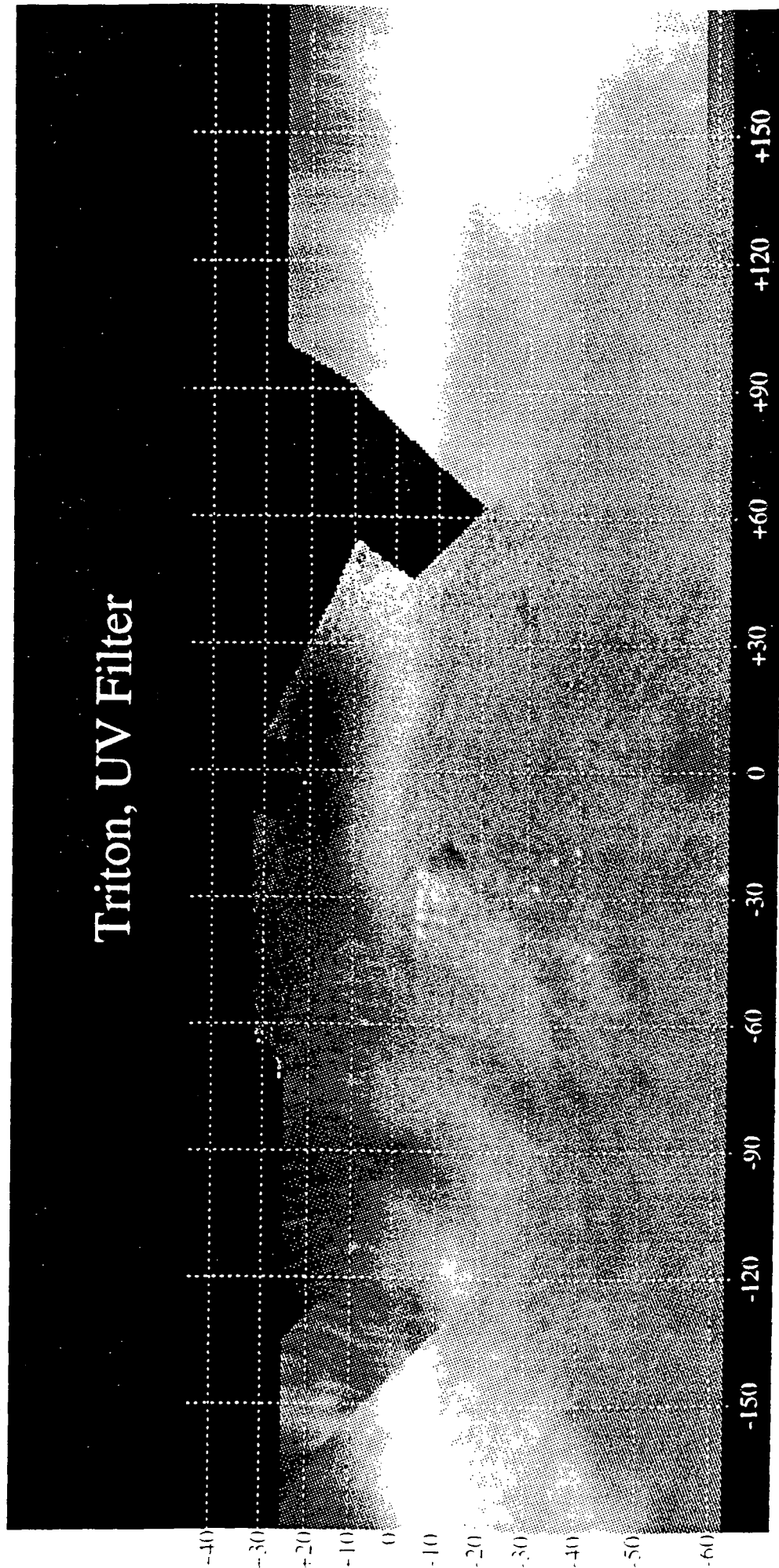


Figure 1a

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Triton, Clear Filter

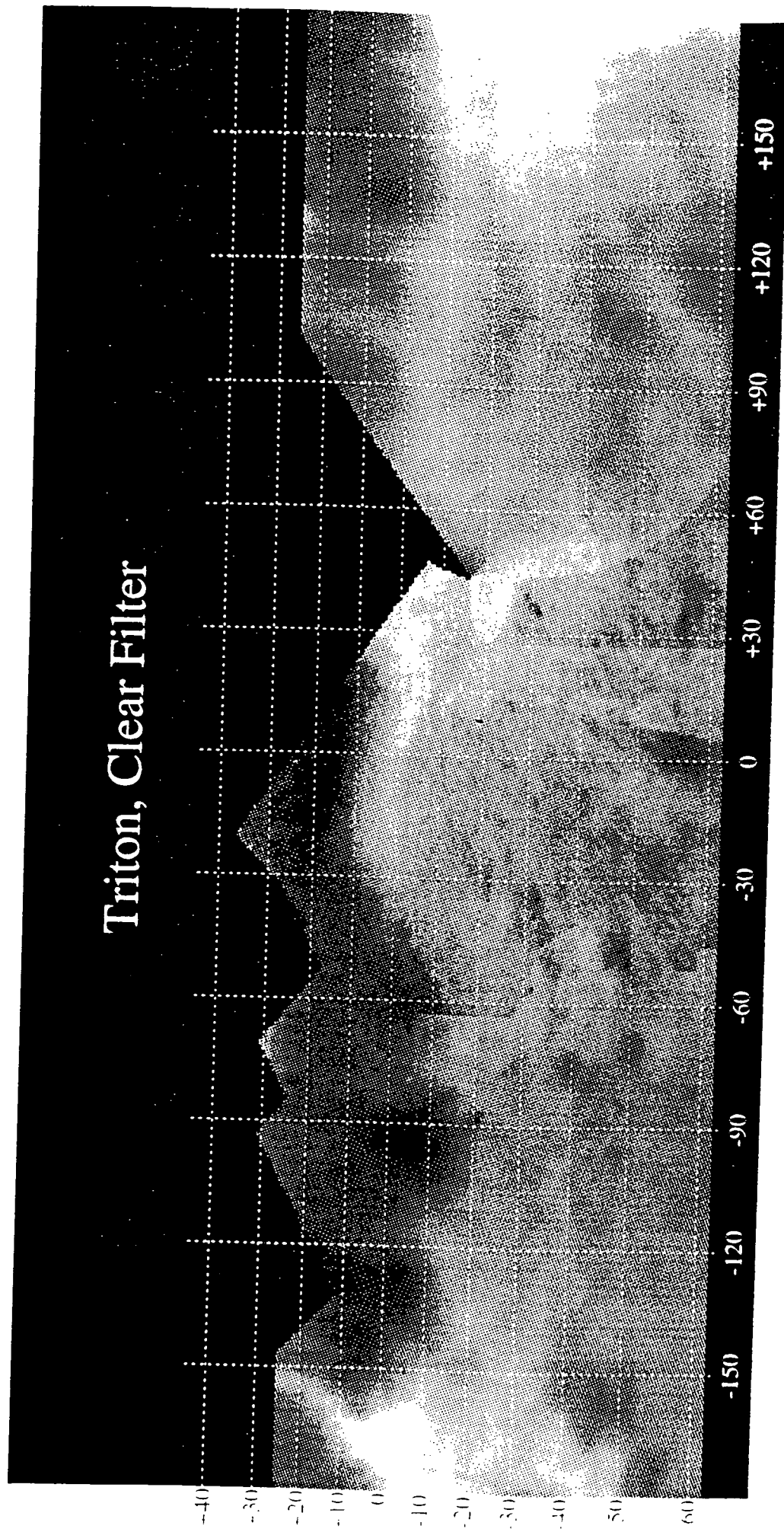


Figure 1b

Clear 5%>Average, UV 5%<Average

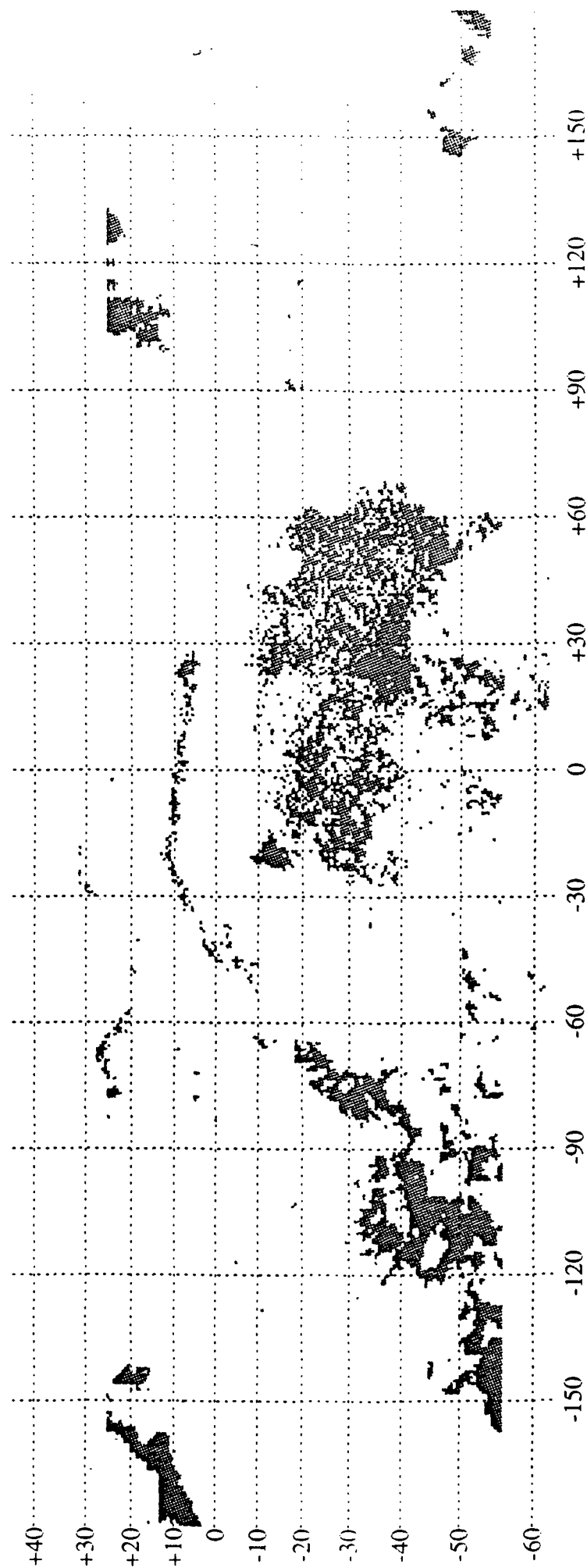


Figure 2a.

Clear, UV 10% > Average

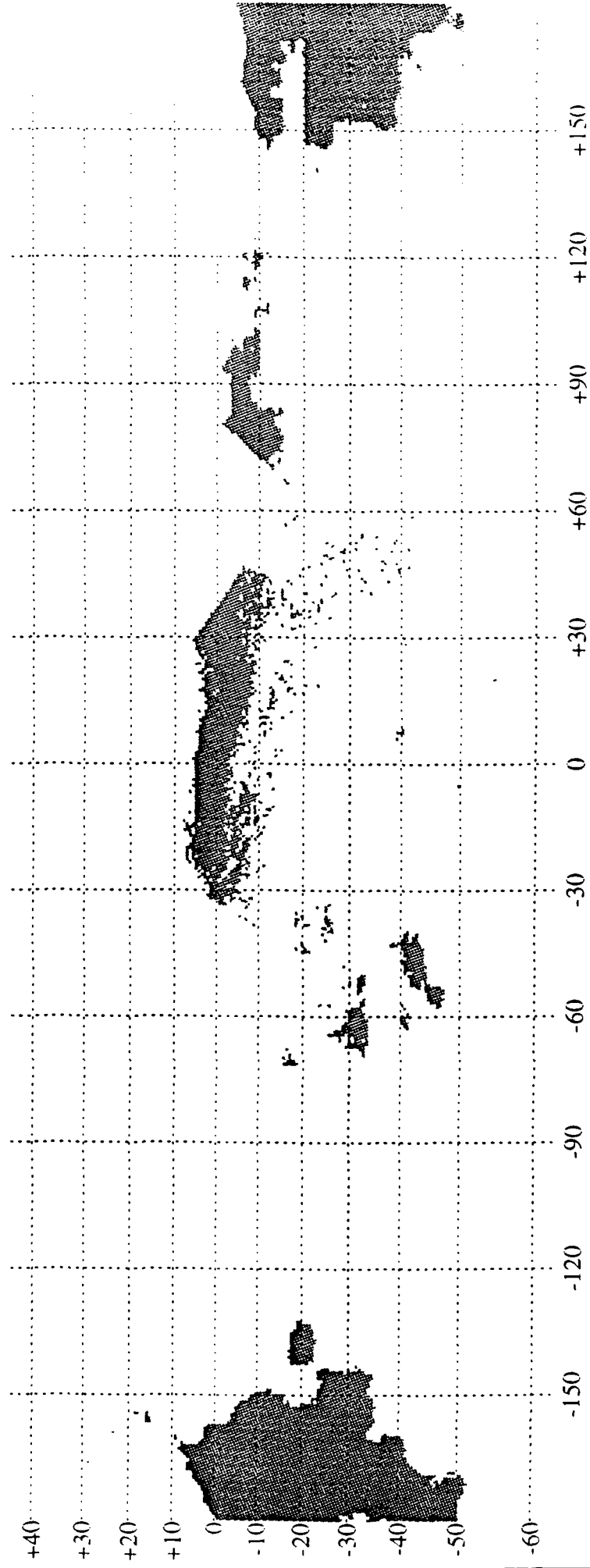


Figure 2b.

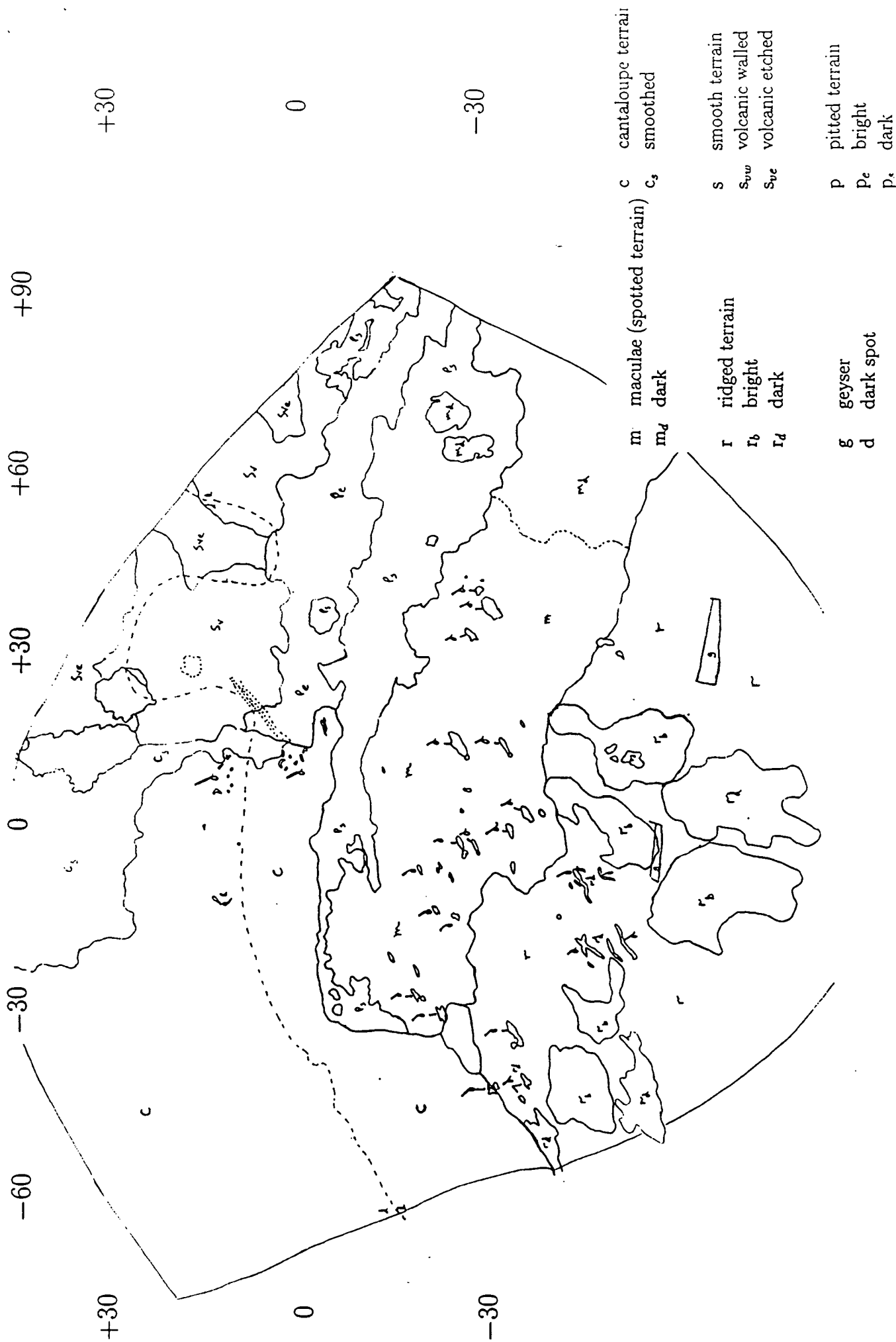
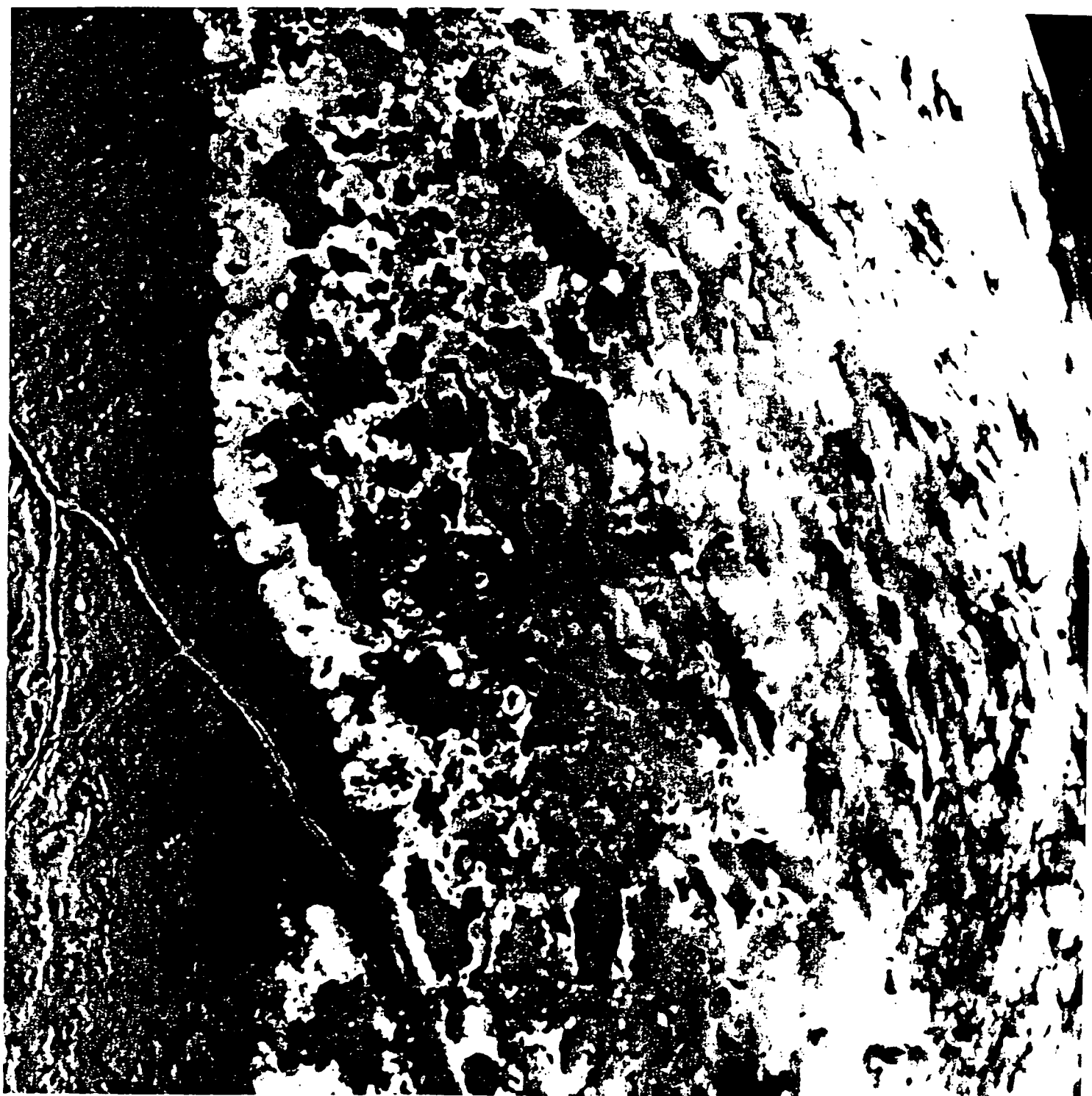


Figure 3.



ROTATIONALLY RESOLVED STUDIES OF THE MID-ULTRAVIOLET SPECTRUM OF TRITON.
II. *HST* SURFACE AND ATMOSPHERIC RESULTS

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ABSTRACT

Using the *Hubble Space Telescope* (*HST*) we have obtained useful spectra of Triton at a resolution of 2 Å from 1900–3278 Å, at five rotational phases in 1992 and 1993. We present these data and analyze them to evaluate the rotational variability of Triton's mid-ultraviolet reflectance spectrum, albedo, and color slope. The main characteristics of Triton's UV reflectance spectrum include: (i) the detection of a rotationally independent cessation in Triton's well-known, red albedo slope near 2750 Å; (ii) the apparent presence of either a blue albedo upturn or a broad, solid-state absorption feature with $\approx 6\%$ depth at this transition wavelength; (iii) the detection of one or additional, broad, presumably solid-state absorption features between 2000 and 2100 Å which may be related to photochemical byproducts of atmospheric chemistry lying on Triton's surface; and (iv) no evidence for atmospheric emissions at this spectral resolution. Regarding the atmosphere, we have analyzed the lack of spectral features due to OH, NO, and CO molecules in the *HST* spectra, in order to provide new constraints on the bulk mixing ratios of these species in Triton's atmosphere. The derived mixing ratio upper limits are $M_{\text{OH}} \leq 3 \times 10^{-6}$, $M_{\text{NO}} \leq 8 \times 10^{-5}$, and $M_{\text{CO}} \leq 1.5 \times 10^{-2}$. These constraints constitute the first-ever data on OH and NO abundance in Triton's atmosphere, and a confirmation that the CO abundance is lower than the initial *Voyager-UVS* upper limit. Returning to Triton's surface, we have found that the main characteristics of Triton's UV rotational light curve derived from these five observations spread in rotational phase include: (i) a monotonically increasing light curve amplitude down to wavelengths as short as 2400 Å; (ii) strong structural similarities in the UV and visible light curves down to 2400 Å; (iii) a sharply reduced light curve amplitude below 2250 Å; and (iv) no indication that the 2750 Å surface absorption feature depth is correlated with rotational phase. These results are interpreted in the text. © 1995 American Astronomical Society.

1. INTRODUCTION

Triton has proven to be one of the most complex and fascinating bodies in the solar system. The 1989 *Voyager 2* encounter with this large satellite of Neptune revolutionized our knowledge of this world. *Voyager 2* revealed Triton to be a scientifically inspiring satellite, 2700 km in diameter, with a cryogenic N_2/CH_4 atmosphere, and a morphologically complex surface (cf. Smith *et al.* 1989; Broadfoot *et al.* 1989; McEwen 1990). Triton's surface pressure is $\approx 14 \mu\text{bar}$; its surface temperature is near 38 K (cf. Tyler *et al.* 1989; Broadfoot *et al.* 1989; Tryka *et al.* 1993). As determined by the *Voyager* UV spectrometer working at wavelengths below 1700 Å, its microbar-class atmosphere is dominated by N_2 gas (Broadfoot *et al.* 1989), but contains traces of CO, CH_4 , and various photochemical byproducts of the $\text{N}_2/\text{CO}/\text{CH}_4$ mixture. *Voyager* also discovered detached hazes, atmospheric emissions excited by the precipitation of charged par-

ticles from Neptune's magnetosphere, and active vents generating plumes that rise almost 10 kilometers into Triton's troposphere.

Since the 1989 *Voyager* investigations, new observational results have added to our knowledge of Triton. Concerning Triton's surface, which is our primary concern in this paper, the most important discoveries are that (i) N_2 , CO, and CO_2 ice have been detected in high resolution IR spectra, and (ii) that the N_2 dominates the surface volatile inventory composition (Cruikshank *et al.* 1993). Concerning surface reflectance, a combination of *Voyager*/visible and *IUE*/ultraviolet measurements show that Triton's light curve amplitude becomes systematically larger at wavelengths below 5600 Å (Hillier *et al.* 1991; Stern *et al.* 1991), indicating the presence of UV-absorbing materials on the surface. These discoveries have increased interest in Triton's surface and atmospheric composition, and have motivated the need for new, *HST*-based UV spectroscopy.

TABLE 1. *HST* Triton observation log.

Observation Mid-Time	Exposure Time	Grating	Triton CML [†]
16.99 May 1992 UT	1453 sec	G270H	137 deg
17.09 May 1992 UT	2908 sec	G190H	144 deg
01.46 Sep 1993 UT	1620 sec	G270H	280 deg
01.58 Sep 1993 UT	4080 sec	G190H	287 deg
02.41 Sep 1993 UT	1620 sec	G270H	343 deg
02.52 Sep 1993 UT	4080 sec	G190H	350 deg
03.41 Sep 1993 UT	1620 sec	G270H	043 deg
03.49 Sep 1993 UT	3060 sec	G190H	048 deg
04.35 Sep 1993 UT	1620 sec	G270H	096 deg
04.45 Sep 1993 UT	4080 sec	G190H	102 deg

[†] CML=Central Meridian Longitude at mid-exposure.

Recently, we reported on the first *Hubble Space Telescope* (*HST*) spectra of Triton, which were taken on 1992 May 16–17 by the *HST* Faint Object Spectrograph (Stern & Trafton 1994). The 2800 Å albedo derived from those data confirmed *IUE* results, obtained in 1988 and 1989, at nearly the same rotational phase. The higher S/N of the *HST* data revealed for the first time that Triton's UV reflectivity loses its red slope below ~2850 Å.

We report here on a much expanded dataset from the Faint Object Spectrograph (FOS). This dataset significantly extends the characterization of Triton's UV surface reflectance properties. The significant improvements relative to previously reported mid-UV spectra of Triton are that the new data (i) have higher S/N, (ii) allow us to expand the available rotational phase coverage to produce the first UV light curves of Triton, and (iii) penetrate the region from 2220 to 1900 Å for the first time.

2. OBSERVATIONS

The *HST* observations reported here were obtained on 1992 May 17 and 1993 September 1–4. In obtaining the 1992 data, we used the FOS's Red digicon detector and the 4.3 arcsec² FOS acquisition aperture. The 1993 spectra were obtained using the same aperture, but with the FOS/Blue digicon detector. During each of the five observations we obtained photons in a 1770–2330 Å bandpass with the G190H grating and a 2220–3278 Å bandpass using the G270H grating. The data were binned onboard the instrument 2:1 in wavelength; as a result, each diode was sampled twice and the resulting spectrum contained 1032 channels. Table 1 gives some additional details about these observations. Table

2 describes the geometric circumstances of the five observations.

All five observation sets were read out every 4 minutes and then summed on the ground. Occasional, single-pixel noise spikes were removed. We custom-reduced the observations to remove potential red leak contamination. The red leak arises from the scattering of light within the instrument, which causes the spectrum at short wavelengths to be contaminated by a small fraction of spectral power scattered from longer wavelengths. This is a particularly important source of background for FOS data obtained with the G190H grating below 1900 Å, but it affects longer wavelength data to a far lesser extent because of the rapidly rising Triton signal. We assumed that the internal scattered-light background was grey and subtracted it from the count rate spectrum before flux calibrations were applied. The maximum count rate was nearly 4 counts/s/diode for the G270H spectrum, at a wavelength of 3250 Å; the minimum count rate was 0.1 counts/s/diode near 2500 Å. By comparison, the FOS background averaged just 0.0034 count/s/diode, which indicates the background is not a significant source of error in the wavelength-binned albedo spectra.

We reduced the FOS spectra using the IDL version of the FOS Instrument Development Team's data reduction package CALFOS. This reduction work included corrections for bad diodes, dark subtraction, flatfielding and vignetting correction, and the determination of the wavelength scales and absolute fluxes. The data were then corrected for instrumental and scattered-light backgrounds, as well as the *HST* response function.

2.1 2220–3278 Å (Grating G270H) Albedo Spectra

To convert the Triton flux spectra to geometric albedo spectra, $p(\lambda)$, we convolved a high-quality, full-disk SUSIM UV solar spectrum made at 0.5 Å resolution on *Spacelab 2* (VanHoosier *et al.* 1988) with a Gaussian to match the effective resolution of the FOS spectrum. Wavelength shifting and stretching of the Triton spectrum at the 1 Å level was required to adequately fit small wavelength calibration problems in the SUSIM spectrum.

At the time of the observations, Triton displayed a negligible solar illumination defect. Geometric albedo was therefore obtained simply by computing

$$p(\lambda) = \frac{D^2 \Delta^2}{R^2} \left(\frac{F_{(\lambda)}}{F_{\text{solar}}(\lambda)} \right) f_{\phi}, \quad (1)$$

TABLE 2. Geometric circumstances for the 1992–1993 *HST* Triton observations.

Mid-Time	Heliocentric Distance (<i>D</i>)	Geocentric Distance (Δ)	Solar Phase Angle (ϕ)
16.99 May 1992 UT	30.19 AU	29.65 AU	1.5 deg
17.09 May 1992 UT	30.19 AU	29.65 AU	1.5 deg
01.46 Sep 1993 UT	30.18 AU	29.52 AU	1.5 deg
01.58 Sep 1993 UT	30.18 AU	29.52 AU	1.5 deg
02.41 Sep 1993 UT	30.18 AU	29.54 AU	1.5 deg
02.52 Sep 1993 UT	30.18 AU	29.54 AU	1.5 deg
03.41 Sep 1993 UT	30.18 AU	29.55 AU	1.5 deg
03.49 Sep 1993 UT	30.18 AU	29.55 AU	1.5 deg
04.35 Sep 1993 UT	30.18 AU	29.56 AU	1.5 deg
04.45 Sep 1993 UT	30.18 AU	29.56 AU	1.5 deg

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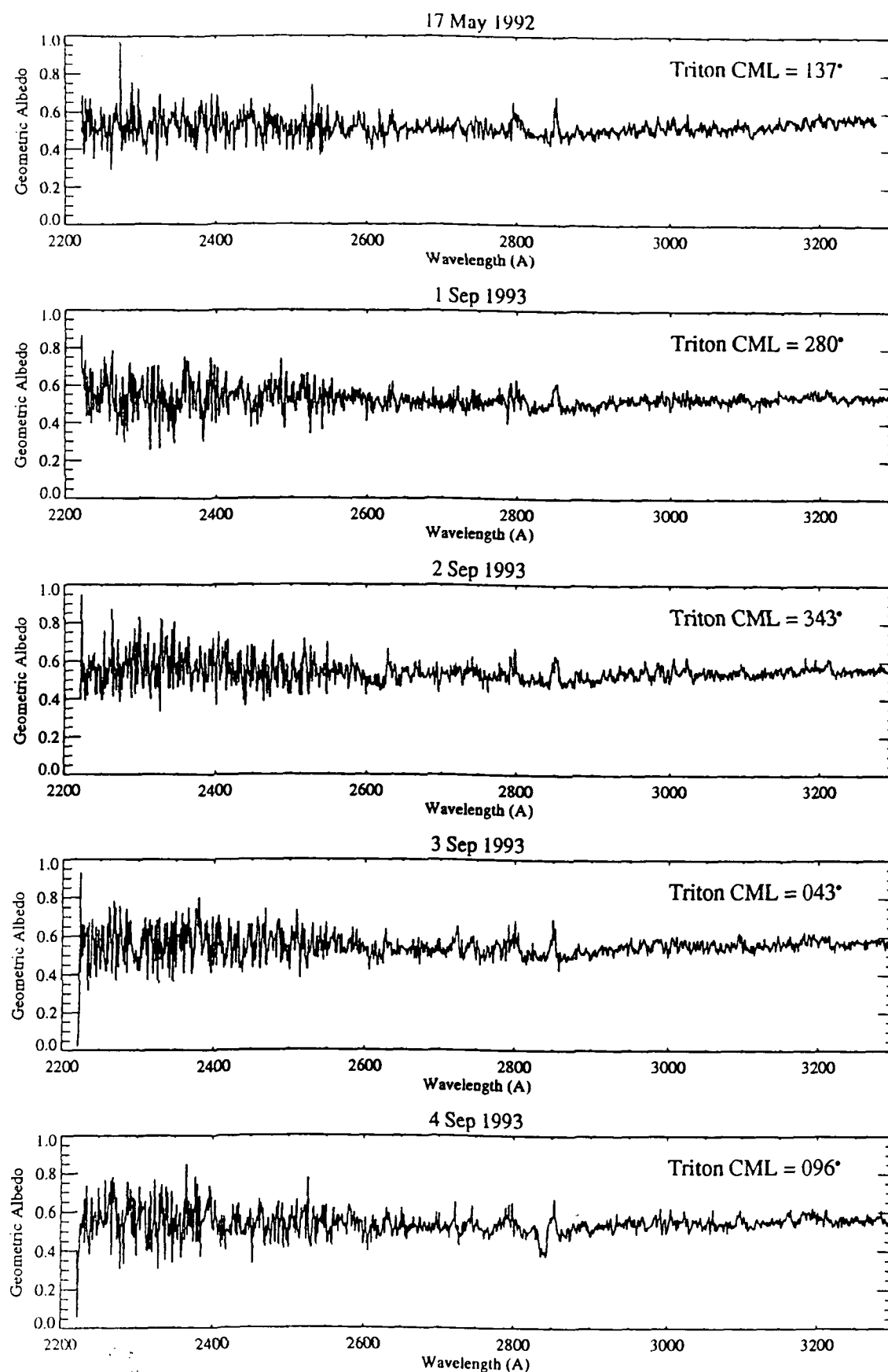


FIG. 1. The five *HST/STIS* geometric albedo spectra of Triton obtained with grating G270H, shown at full spectral resolution, in the order that the observations were taken with their Triton Central Meridian longitude (CML) given.

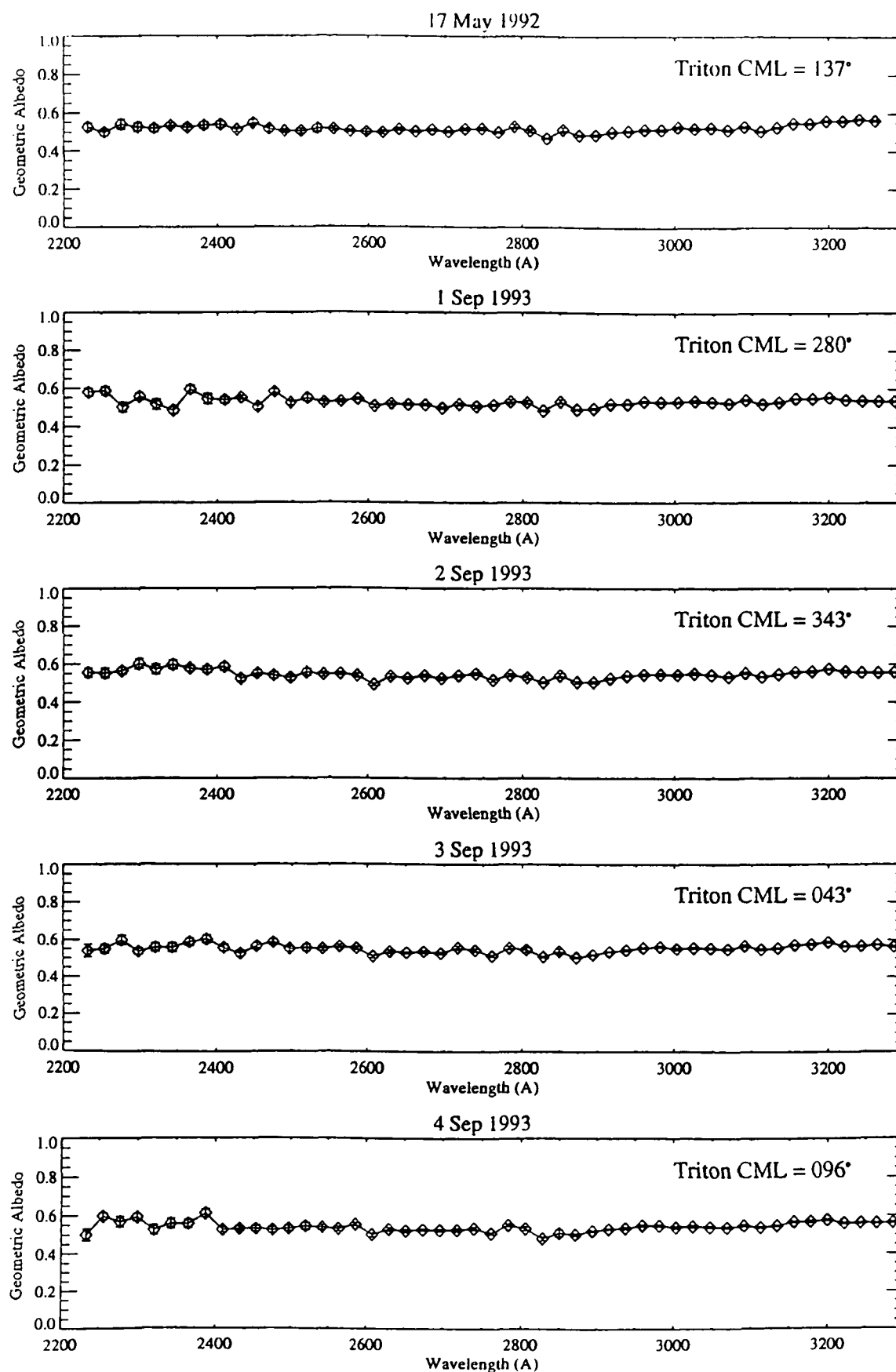


FIG. 2. The five *HST/FOS* albedo spectra of Triton obtained with grating G270H, shown at a binned spectral resolution of 22 Å. The errors bars, which are often smaller than the plot symbols, are the standard deviation of the mean in each plotted bin.

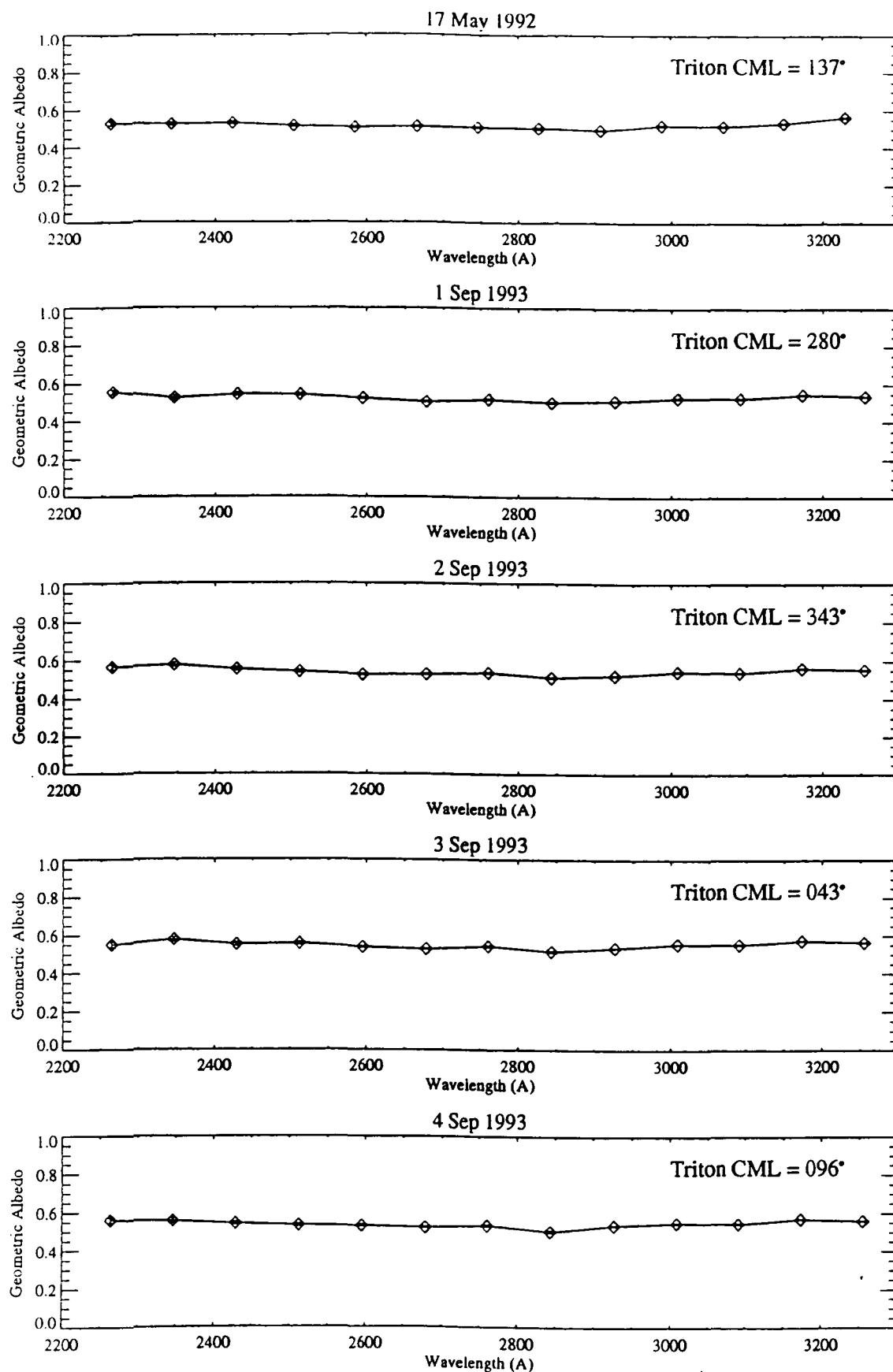


FIG. 3. The five *HST*/FOS albedo spectra of Triton obtained with grating G270H, shown at a binned spectral resolution of 82 Å. The errors bars, which are often smaller than the plot symbols, are the standard deviation of the mean in each bin.

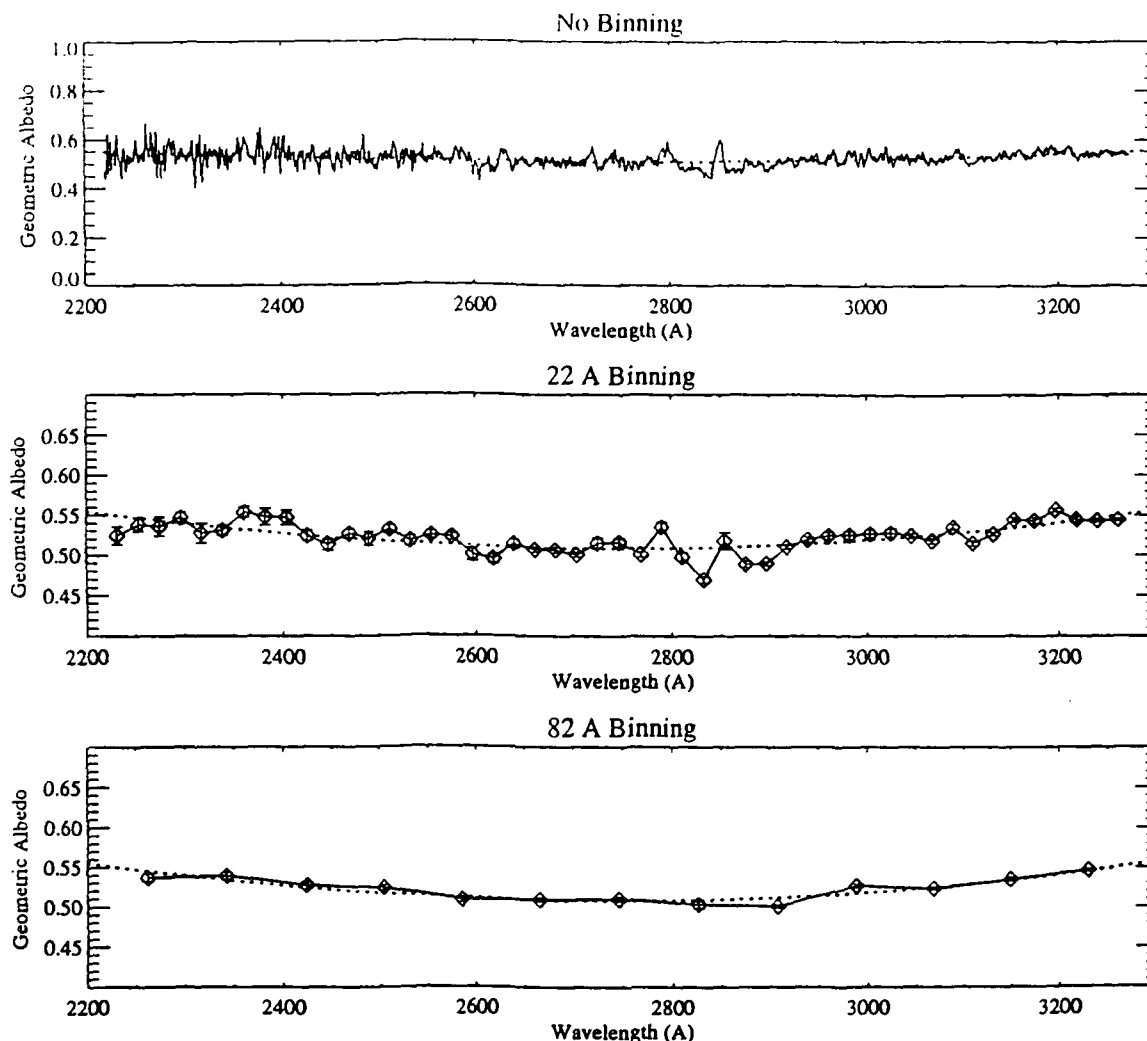


FIG. 4. The grand-sum average of all five *HST*/FOS albedo spectra of Triton obtained with grating G270H, shown at full, 22 and 82 Å resolution. In each case, the errors bars, which are often smaller than the plot symbols, are the standard deviation of the mean in each bin. Notice the lower two panels are shown in an expanded scale to best depict the broad 2750 Å absorption feature. The dotted lines in each panel represent the quadratic fits we obtained to the 2750 Å feature.

where D is the average heliocentric distance in AU during the given observation, Δ is the average geocentric distance during the observation, f_ϕ is the correction factor to normalize the geometry to zero solar phase angle, R is the radius of Triton (1350 km; Smith *et al.* 1989), $F_{\text{solar}}(\lambda)$ is the solar flux at 1 AU, and $F(\lambda)$ is the *HST*-measured flux at wavelength λ . To compute f_ϕ we employed Lane *et al.*'s (1989) *Voyager*-derived 2500 Å, linear phase correction coefficient of 0.011 mag/deg.

Figure 1 depicts the geometric albedo spectrum derived by applying the algorithm in Eq. (1) to all five sets of FOS/G270H data. The features near the Mg and Mg⁺ 2800 and 2850 Å are artifacts due to a misregistration between the data and the archival solar spectrum in this region. This misregistration itself results from temporal variations in the solar Mg and Mg⁺ Fraunhofer lines. The general decrease in S/N toward the blue end of the G270H data is primarily caused by the steeply decreasing solar flux. Figures 2 and 3 present the same data rebinned at resolutions of 22 and 82 Å, respectively. The error bars shown in these two figures are the standard deviation of the mean in each wavelength bin.

Inspecting Figs. 1–3, one detects the clear cessation of the red, (i.e., positive) albedo slope that is so prominent in Triton's IR, visible, and near-UV spectrum. Our analysis convinces us that this is not due to Neptune-scattered light, since (i) it shows no correlation with Triton's distance from Neptune, and (ii) the UV light curves at $\lambda > 2500$ Å (which we derive in Sec. 5 below) show such strong structural similarities to visible-wavelength light curves derived from *Voyager* data. Notice the cessation of Triton's red albedo slope occurs near 2750 Å in all five rotational epochs, and that below ≈ 2750 Å, Triton's albedo slope becomes blue (i.e., it acquires a negative slope) at all five rotational epochs. The qualitatively similar red and blue slope regions on either side of the 2750 Å slope transition suggest the possibility of a broad, solid-state spectral absorption feature in Triton's surface reflectance spectrum.

Figure 4 presents a grand-sum average of the G270H data at all five rotational epochs at the same three spectral resolutions shown in Figs. 1–3: no binning, 22 Å binning, and 82 Å binning. The dotted line in each panel of Fig. 4 is a qua-

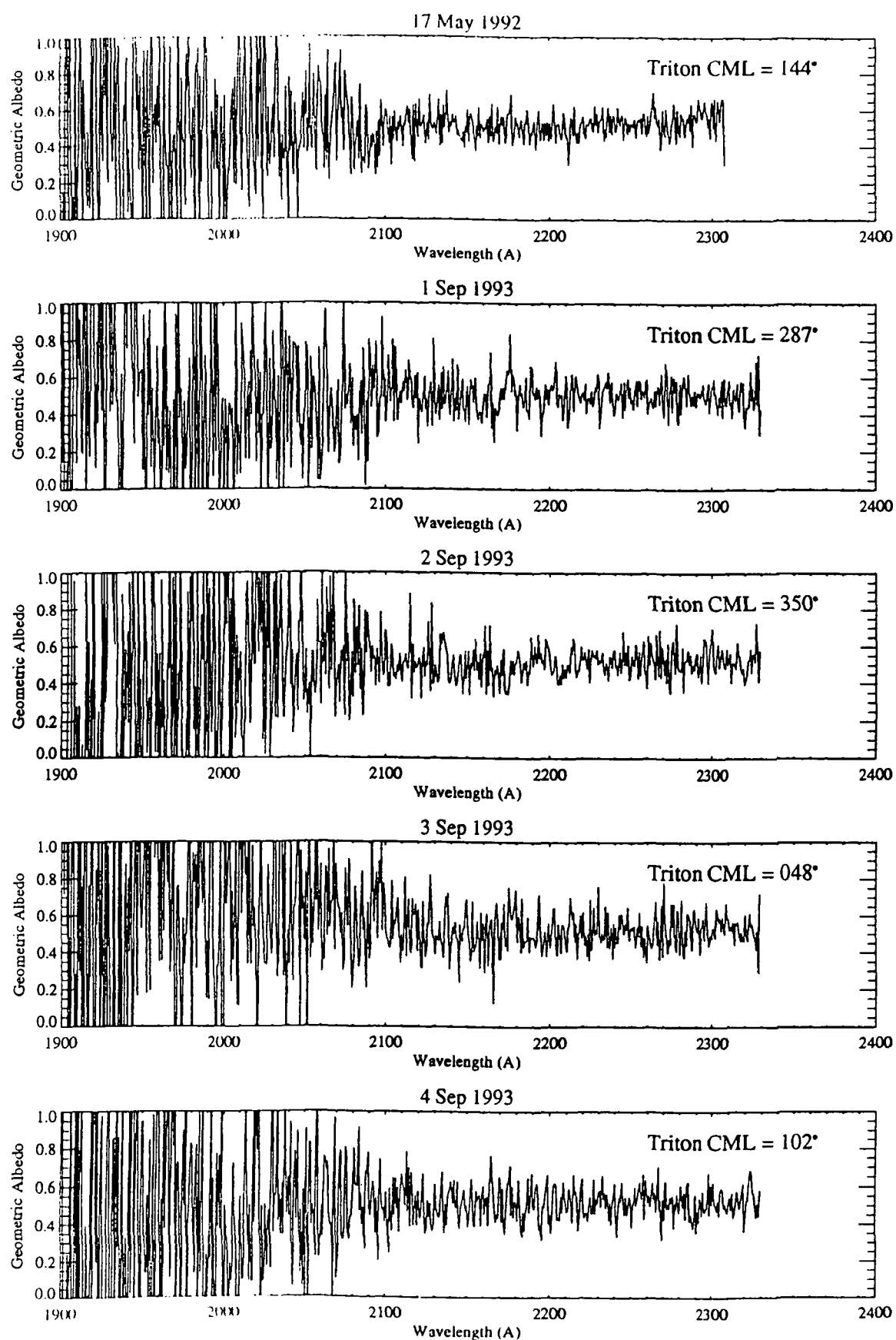


FIG. 5. The five *HST* FOS geometric albedo spectra of Triton obtained with grating G190H, shown at full spectral resolution.

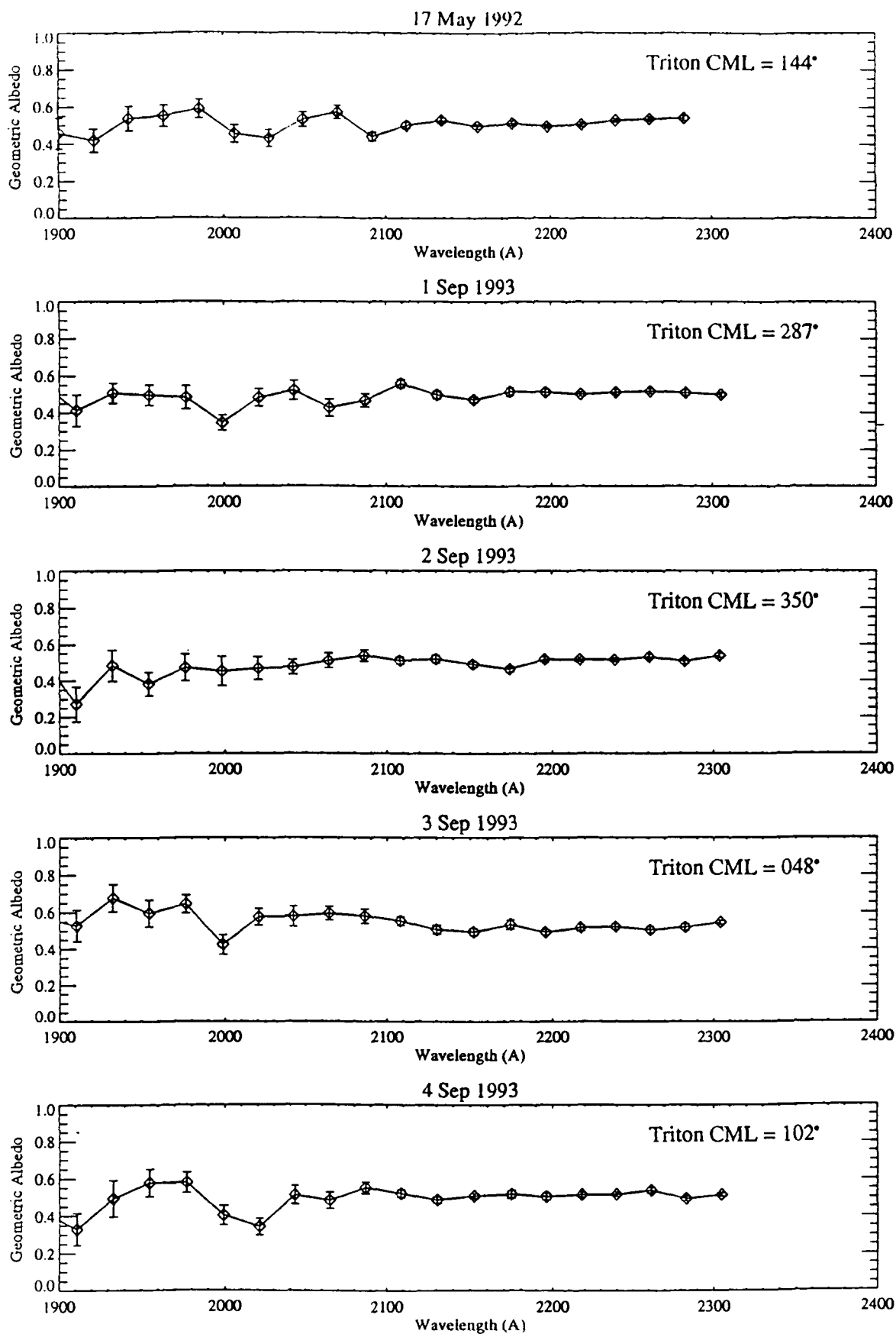


FIG. 6. The five *HST*/FOS albedo spectra of Triton obtained with grating G190H, shown at a binned spectral resolution of 22 Å. The errors bars are the standard deviation of the mean in each bin. Note the strong absorption feature centered near ≈ 2000 .

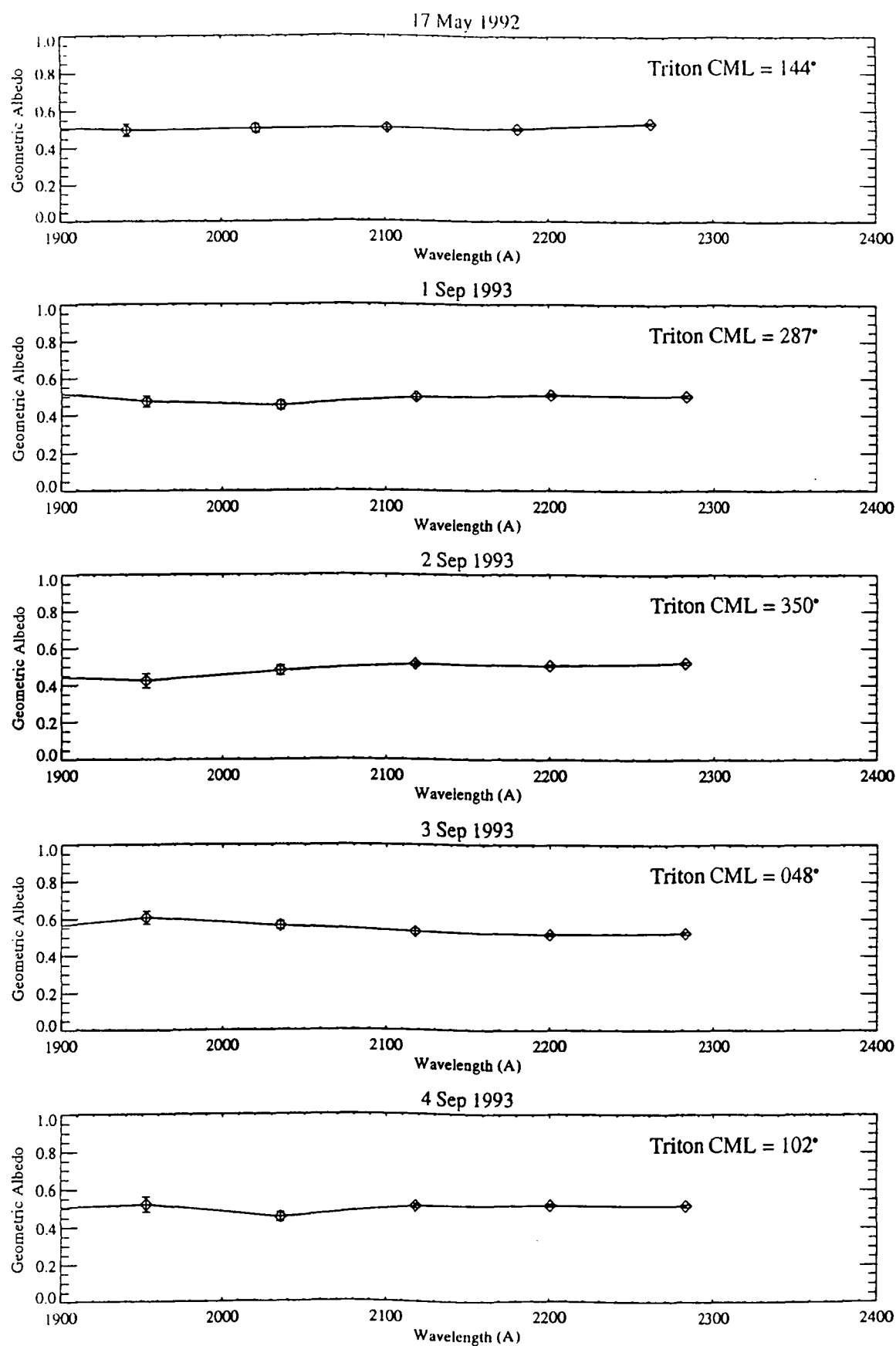


FIG. 7. The five *HST*/FOS albedo spectra of Triton obtained with grating G190H, shown at a binned spectral resolution of 82 Å. The error bars shown are the standard deviation of the mean in each bin.

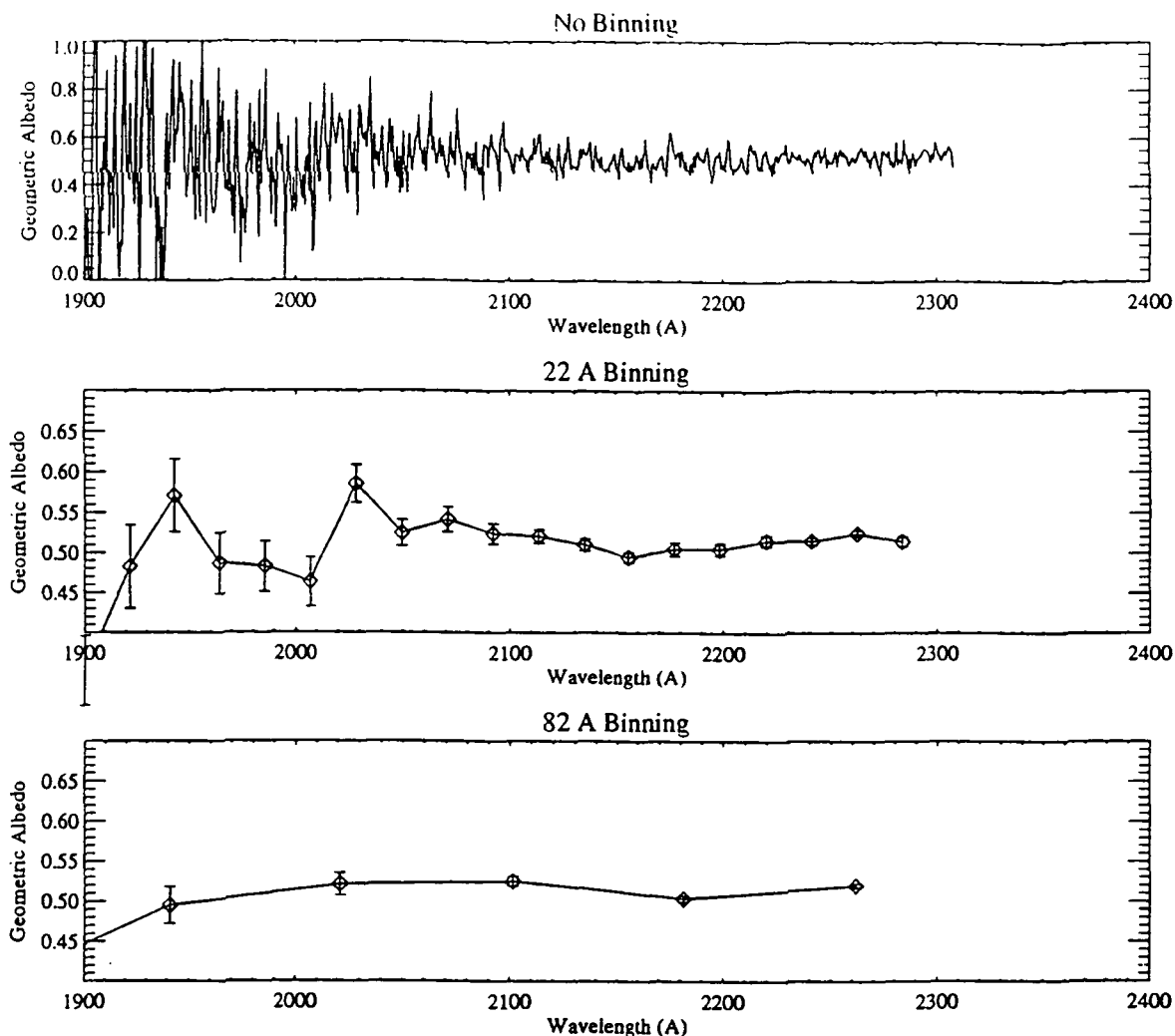


FIG. 8. The grand-sum average of all five *HST*/FOS albedo spectra of Triton obtained with grating G190H, shown at full, 22, and 82 Å resolution. In each case the errors bars shown are the standard deviation of the mean in each bin. Notice the lower two panels are shown at an expanded scale.

dratic fit to the data. At the 22 Å resolution, a 2750 Å band depth of $\approx 5.9 \pm 2.8\%$ was found, relative to the "reference continuum" levels at 2300 and 3200 Å. In the higher S/N data binned at 82 Å resolution, a 2750 Å band depth of $\approx 6.0 \pm 0.8\%$ was found. This feature is most likely generated by a non-icy contaminant on Triton's surface. Because no statistically significant modulation in the band depth or shape was detected as a function of rotational phase, we conclude that the surface component responsible for this feature is approximately uniformly distributed on the surface.

These UV spectra are useful in another way; namely, for the study of rotational variations in Triton's UV surface reflectance. Before proceeding to such analyses, however, we will first describe the short-wavelength (i.e., 1900–2330 Å) *HST*/FOS spectra we obtained at the same rotational epochs as the G270H spectra we have just described.

2.2 1900–2330 Å (Grating G190H) Albedo Spectra

Figure 5 depicts the full-resolution geometric albedo spectrum derived by applying the algorithm in Eq. (1) to all five FOS/G190H Triton spectra that have been obtained. These spectra were acquired on the same dates as the FOS/

G270H spectra described in the previous section. Figure 5 the short-wavelength companion to Fig. 1. As in the G270H data, the clear decrease in S/N toward the blue end of the G190H bandpass is caused by a combination of instrument efficiency loss and steeply decreasing solar flux. Figures 6 and 7 present the same G190H data, rebinned at resolution of 22 and 82 Å, respectively. As in Figs. 1–3, the error bars shown are the standard deviation of the mean in each wavelength bin.

The presence of data spikes to 0 and >1 albedo in the full-resolution, Fig. 5 data indicate that these albedo data are not reliable below 2100, or perhaps 2050 Å. The coarser 22 and 82 Å binnings shown in Figs. 6 and 7 were made from the Fig. 5 data after omitting all albedo values ≤ 0 and ≥ 1 .

Figure 8 presents grand-sum averages of the G190H data from all five rotational epochs; these grand sums are depicted at the raw, 22 and 82 Å resolutions. By averaging the five G190H spectra, we have been able to extend the grand-sum wavelength coverage blueward to 1900 Å.

Examining the spectra presented in Figs. 5–8, we conclude that (i) no statistically significant, wavelength-correlated spectral emissions are observed in the five G190

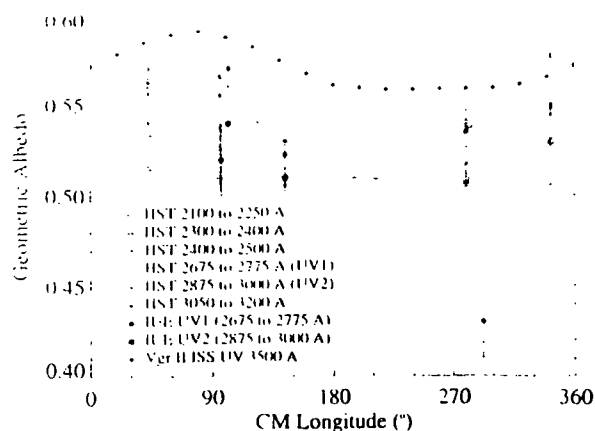


FIG. 9. The five-point albedo light curves of Triton obtained from the *HST* geometric albedo spectra, shown in the six indicated UV bandpasses. Also shown are the available *IUE* data and the *Voyager 2* imaging-derived 3500 Å light curve.

spectra, (ii) Triton's albedo slope is neutral or red between 2000 and 2300 Å, and (iii) the spectra shown at 22 Å resolution spectra appear to show a significant (i.e., $\approx 20\%$ relative), broadband absorption feature (or complex of features) between 2000 and 2100 Å.

The absorption feature detected between 2000 and 2100 Å is present at four of the five rotational aspects, but seems to change its detailed character as a function of rotational aspect. This absorption complex may be related to the long-suspected surface deposits of CH_4/N_2 -radiation chemistry byproducts, which are believed to also generate Triton's visible- and near-UV red color slope. Such byproducts include C_2 -hydrocarbons, HC_3N , and other nitriles which manifest various broad (80–200 Å) absorptions between 1800 and 2500 Å.

2.3 Triton's First-Order UV Rotational Light Curves

In this section we examine the variation in the five *HST* spectra of Triton acquired to date to obtain the characteristics of Triton's UV rotational light curve. Since only five rotational epochs are available at the present, we call the resulting data products a "first-order" UV rotational light curve. Although no new *HST* UV spectra or images of Triton have been obtained since 1993, we believe the first-order light curves obtained here will be useful for some time. However, we caution the reader that new data may reveal high spatial frequency features that this initial dataset cannot.

To begin our examination of Triton's UV light curve, Fig. 9 presents the five-point UV light curves in six broad wavelength bins between 2100 and 3200 Å. Again, the depicted error bars are the standard deviations of the mean for each plotted bin. Also depicted in this figure are the available *IUE* points (cf. Stern *et al.* 1989, 1991) and the *Voyager*-derived 3500 Å light curve (Hillier *et al.* 1991).

Notice in Fig. 9 that all the wavelength bins except the 2100–2250 Å bin show similar rotational behavior, characterized by a broad maximum between ≈ 30 and 70 deg longitude, a significant decline between ≈ 90 and 135 deg, and a broad, almost-flat trough between ≈ 135 and 270 deg.

In contrast, the 2100–2250 Å bandpass shows little rotational variation. This lack of contrast is similar in both the G190H and G270H spectra, which overlap this wavelength region. The lack of rotational variation in the 2100–2250 Å bandpass is primarily ascribable to the lack of the visible- and UV-bright feature in the ≈ 330 to 70 deg longitude range on Triton's leading side. This is also the longitude range where the greatest contribution of polar cap deposits and bright polar fringe terrain are visible, and where the anomalous scattering region was first noted by Lee *et al.* (1992).

The most important conclusion one reaches from the dramatically different structure and amplitude of the 2100–2250 Å *HST* light curve is that the rotationally resolved appearance of Triton undergoes a significant transition between 2200 and 2300 Å. Shortward of ≈ 2250 Å, Triton's light curve becomes significantly muted, and its average albedo changes by more than in any other bandpass we have studied between 2000 and 9000 Å (the change is about -12% in relative terms, -0.06 in geometric albedo). We interpret these changes as evidence that one of the bright frost components on Triton's surface suffers a sharp drop in reflectivity below ≈ 2200 Å that is sufficient to (i) decrease the average albedo a few percent and (ii) cause the contrast in Triton's UV appearance to largely disappear. These changes can also be seen by comparison of the individual spectra shown in Figs. 5–7.

Now we compare the *IUE* data obtained in 1988 and 1989 to the *HST* data obtained in 1992 and 1993. Notice that the *IUE* and *HST* data agree well near 90 degrees, but differ substantially near 270 deg. After a re-examination of the *IUE* data, we attribute this discrepancy to the faulty removal of Neptune-scattered light in the *IUE* TR7 spectrum. This correction implies that the large, 12%–14% UV1 rotational variation found by Stern *et al.* (1991) was overestimated by a factor of about two.

We now turn to a comparison between the six 2100–3200 Å (mid-UV) *HST* light curves derived here, and the six 3500–5800 Å (visible and near-UV) *Voyager 2* light curves that Hillier *et al.* (1991) derived from global imaging. All six of Hillier *et al.*'s light curves are broadly similar to one another. For convenience, we overplotted only the Hillier *et al.* 3500 Å light curve in Fig. 9. The strong, qualitative similarity in the longitudinal structure of the *HST* and *Voyager* light curves is striking. In ten consecutive bandpasses between 2400 and 5800 Å, Triton displays a similarly shaped, asymmetric, distinctly nonsinusoidal light curve which (i) peaks in geometric albedo between ≈ 60 and 100 deg, (ii) transitions to a lower albedo between ≈ 100 and 180 deg, and then (iii) exhibits a broad trough extending from ≈ 200 to 330 deg. Although some differences in the locations of the *HST* and *Voyager* light curve maxima and minima are apparent, the small number of rotational points available from *HST* suggests these differences may not be significant. The main conclusion to be drawn from the similarity of the light curve structure over the 10 bandpasses is that Triton's large-scale color units remain relatively constant between 2400 and 5800 Å.

In contrast to the structural similarities of the light curves over this broad wavelength regime, a clearly detectable light

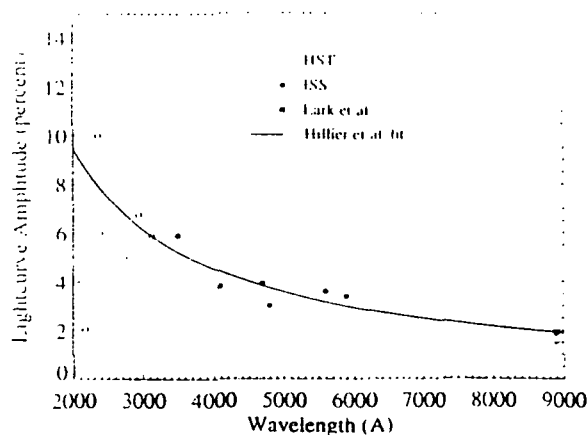


FIG. 10. The detected Triton light curve amplitudes obtained from the *HST* albedo spectra, shown in six UV bandpasses of Fig. 9. The *HST*-derived light curve amplitudes shown are lower limits in that our light curves are not dense, and somewhat higher light curve amplitudes may ultimately be discovered in a rotationally denser dataset. Also shown are the *Voyager*-derived visible and near-UV light curve amplitudes developed by Hillier *et al.* (1991), the 8900 Å upper limit derived by Lark *et al.* (1989), and the Hillier *et al.* (1991) light curve amplitude fit as a function of wavelength.

curve amplitude trend is seen as one moves from the visible to the mid-UV. By amplitude, we mean the percentage difference between the maximum and minimum measured geometric albedos in each wavelength bin.

Figure 10 depicts the amplitude of the five-point light curves in each of the six wavelength bins. We conservatively refer to these as "lower limit" amplitudes because our rotational phase coverage is sparse. We caution, however, that because our phase coverage is relatively complete, we do not expect Triton's hemispherically averaged UV light curve amplitude to dramatically exceed the values depicted.

In Fig. 10 we also depict the amplitude of the *Voyager*-derived light curves between 3500 and 5800 Å, and the fit that Hillier *et al.* obtained to model the systematic increase in light curve amplitude with decreasing wavelength in the *Voyager*-derived data. The Hillier *et al.* fit appears to be applicable to wavelengths as short as 2400 Å; however, to confirm this, additional UV data must be obtained by *HST*, particularly between Triton longitudes 330 and 120 deg. In any case, the 2300–2400 Å and 2100–2250 Å *HST* light curve amplitudes demonstrate that the *Voyager*-derived light curve amplitude function (Hillier *et al.* 1991) apparently ceases to be valid below ~2400 Å.

The change in Triton's light curve below 2300 Å is apparently due to the absence of the pronounced albedo maximum extending from ~330–090 deg seen at longer wavelengths. We speculate that either (a) some bright material with low (e.g., perhaps 10%) areal coverage in this region undergoes a sharp drop in albedo to some near-zero level or (b) some material with wider (e.g., 50%) areal coverage in this region decreases in albedo by a much more moderate amount (e.g., 10%).

We now turn to our last result concerning Triton's UV surface reflectance properties. This is shown in Fig. 11, which depicts the fractional change in Triton's color slope as a function of rotational phase (or equivalently, central meridian longitude). Owing to the inherently noisier nature of

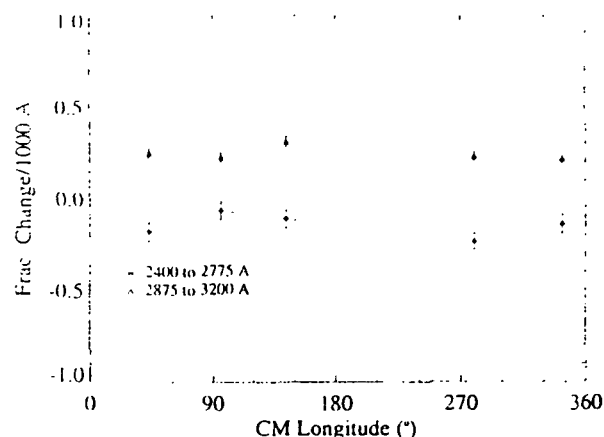


FIG. 11. Five-point UV color-variation light curves of Triton obtained from the albedo spectra, shown in three broad UV bandpasses.

color slopes, which are derived by differentiation of albedo data, we were unable to derive statistically meaningful results in the six narrow bandpasses used to create the rotational light curves in Figs. 9 and 10. Instead, we found it necessary to use three wider bandpasses for studies of color slope variations. The bands we chose were 2200–2400 Å, 2400–2775 Å, and 2875–3200 Å.

In the 2200–2400 Å color bandpass, one finds both much steeper slopes and much more dramatic color slope changes with rotational phase than in the two longer wavelength color bandpasses. In the 2875–3200 Å bandpass, the color slope is always negative (i.e., red). In the 2400–2775 Å region, the color slope is consistently positive (i.e., blue). In both of these bandpasses, the color slopes (i) vary by factors of two with rotational phase, and (ii) are generally anticorrelated. The latter result implies that, for the most part, regions where the red slope is steepest (or shallowest), the blue slope is similarly steep (or shallow, respectively), and suggests that the band depth of the 2750 Å absorption feature is correlated with rotational phase.

2.4 Constraints on OH, NO, and CO in Triton's Atmosphere

In addition to studies of Triton's UV surface reflectance, the *HST*/FOS spectra are also useful for constraining the abundances of several molecules in Triton's atmosphere, particularly the O-bearing species OH, NO, and CO.

No O-bearing species has yet been detected in Triton's atmosphere. This begs several important questions about Triton's origin; its surface-atmosphere interaction, and its atmospheric chemistry. Three of the most likely O-bearing candidates, OH, NO, and CO can be searched in our FOS data. NO and OH could result from CO–CH₄–N₂ or H₂O–CH₄–N₂ chemistry; CO, which has been detected as a frost in surface reflectance spectra in the IR, is expected to sublime into Triton's atmosphere, but its atmospheric abundance is unknown.

We have carefully inspected the FOS data for evidence of discrete spectral emission and absorption features that might

believe the presence of OH, NO, and CO. Our primary technique was to search for each species in absorption, however, because this technique takes advantage of (rather than fighting) the surface albedo, and is able to increase S/N by binning over several FOS diodes to match the FWHM of the bands. No features were detected. In what follows we determine the detection limits and briefly discuss the implications of the derived constraints for each of these molecules.

2.4.1 OH

One plausible path to OH production is CO-CH₄ photochemistry. A second plausible path would be through the dissociation of meteoritic-H₂O. In either case, the OH abundance provides clues to both the H₂O and total oxygen abundance in Triton's atmosphere, and therefore the atmospheric redox state.

Our derivation of an OH upper limit proceeds as follows. For the strong OH (0-0) band, at 3085 Å, Okabe (1978) gives an absorption cross section of 7×10^{-18} cm². In the highly binned, low-resolution grand-sum spectra presented in Fig. 4, we achieved a S/N near 10 in the 0-0 band. It should thus have been possible to detect a 20% percent OH (0-0) absorption at 10 σ confidence. For an optically thin, 10 μ bar atmosphere at 100 K, this upper limit corresponds to an atmospheric OH mixing ratio constraint near 3×10^{-5} .

2.4.2 NO

Neither *Voyager* (owing to limited spectral bandpass), nor *IUE* (owing to limited sensitivity) could have detected the strong NO γ bands at 2149, 2263, and 2363 Å that may be formed in Triton's atmosphere. Okabe (1978) has given an absorption cross section for the strongest of these (at 2149 Å) of 5×10^{-19} cm². Accounting for the ≈ 4 diode-width of the bands, we estimate our grand-sum FOS/G190H exposure could have detected a 40%-deep NO band absorption with 7 σ confidence against the adjacent albedo continuum. For the same assumptions about the neutral atmosphere column described in the OH discussion immediately above, this upper limit corresponds to an NO mixing ratio constraint near 8×10^{-5} .

2.4.3 CO

As noted above, although absorption features attributable to CO frosts on Triton's surface have now been detected at the IRTF (Cruikshank *et al.* 1993), there is no detection of CO in Triton's atmosphere. This is most likely due to the almost two orders of magnitude lower surface abundance of CO, relative to N₂, that Cruikshank *et al.* derived.

Owing to interpretation questions (Gladstone, private communication), upper limits (Broadfoot *et al.* 1989) as great as 20% appear consistent with the *Voyager 2* UVS upper limit on atmospheric CO. To improve on this constraint, we searched for CO absorption using the (1-0) Cameron

band at 1989 Å and the (0-0) band at 2063 Å (cf. Okabe 1978). The stronger, (0-0) band has an absorption cross section of roughly 3×10^{-21} cm² at the resolution of the FOS spectra. Using this cross section, we estimate that the grand-sum FOS/G190H spectrum presented in Fig. 8 could have detected a 40% absorption band depth (corresponding to a CO column of $\approx 2 \times 10^{20}$ cm⁻²) at 3.5 σ against the albedo continuum at 2063 Å. This corresponds to an atmospheric CO mixing ratio of $M_{\text{CO}} = 0.015$. The lack of a CO absorption band at 1989 Å corroborates the nondetection at 2063 Å.

This newly derived observational upper limit lends further support to Krasnopolsky *et al.*'s (1993) model results, which concluded that Triton's tropopause [CO]/[N₂] mixing ratio could be no higher than 0.01, or cooling by CO would violate constraints on Triton's thermospheric heat flux.

3. CONCLUSIONS

Using *HST*, we have completed the first survey of Triton's mid-ultraviolet reflectance properties, adding important new insights that *IUE* could not obtain.

We have found that the main characteristics of Triton's UV reflectance spectrum include: (i) a rotationally independent cessation in Triton's well-known, red color slope near 2750 Å; (ii) the apparent presence of either a blue albedo upturn or a broad, solid-state absorption feature with $\approx 6\%$ depth at this transition wavelength; and (iii) the detection of one or additional, broad, presumably solid-state absorption features between 2000 and 2100 Å which may be related to photochemical byproducts of atmospheric chemistry lying on Triton's surface. We have also found that the main characteristics of Triton's UV rotational light curve derived from these five observations spread in rotational phase include: (i) a monotonically increasing light curve amplitude down to wavelengths as short as 2400 Å; (ii) strong structural similarities in the UV and visible light curves down to 2400 Å; (iii) a sharply reduced light curve amplitude below 2250 Å; and (iv) no indication that the 2750 Å surface absorption feature depth is correlated with rotational phase. These results are interpreted in the text.

In addition to the surface reflectance results, we have also used the *HST*/FOS spectra to obtain upper limits on three oxygen-bearing species in Triton's atmosphere, OH, NO, and CO. The derived mixing ratio upper limits are $M_{\text{OH}} \leq 3 \times 10^{-6}$, $M_{\text{NO}} \leq 8 \times 10^{-5}$, and $M_{\text{CO}} \leq 1.5 \times 10^{-2}$. These constraints constitute the first-ever data on OH and NO abundance in Triton's atmosphere, and a confirmation of Krasnopolsky *et al.*'s (1993) finding which improved on the initially published *Voyager* UVS CO upper limits by over an order of magnitude.

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